Global Scale Energy Fluxes: Comparison of Observational Estimates and Model Simulations

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CERES Science Team Meeting
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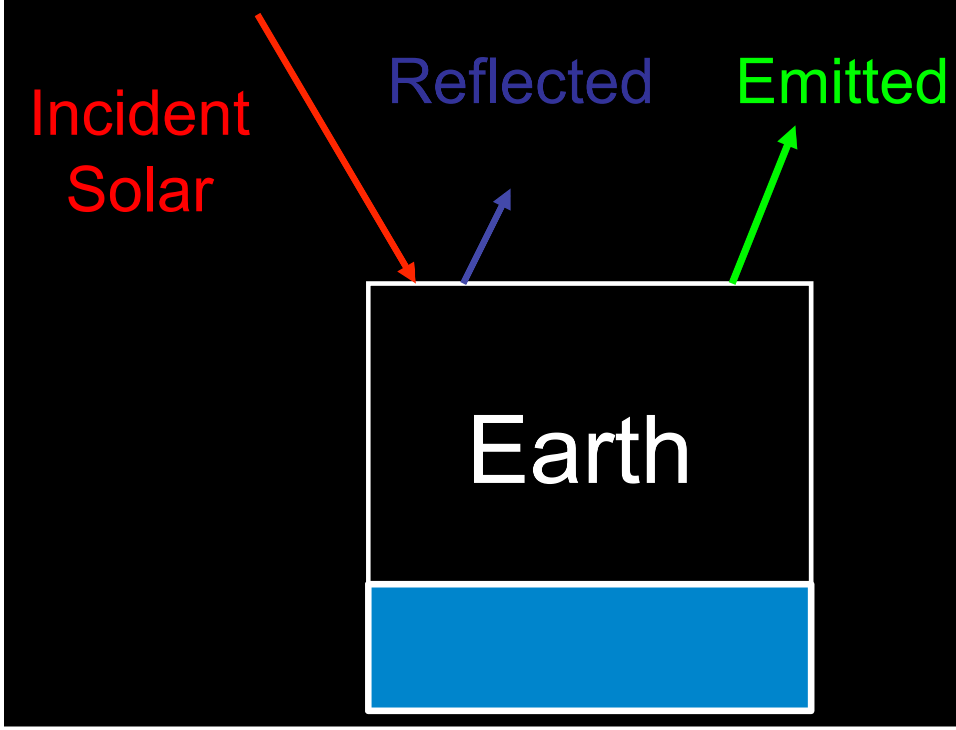
Global mean energy balance

- The Earth receives energy from the sun (and reflects back some portion of it)
- To come into energy balance (equilibrium) the Earth must emit the same amount of energy it receives

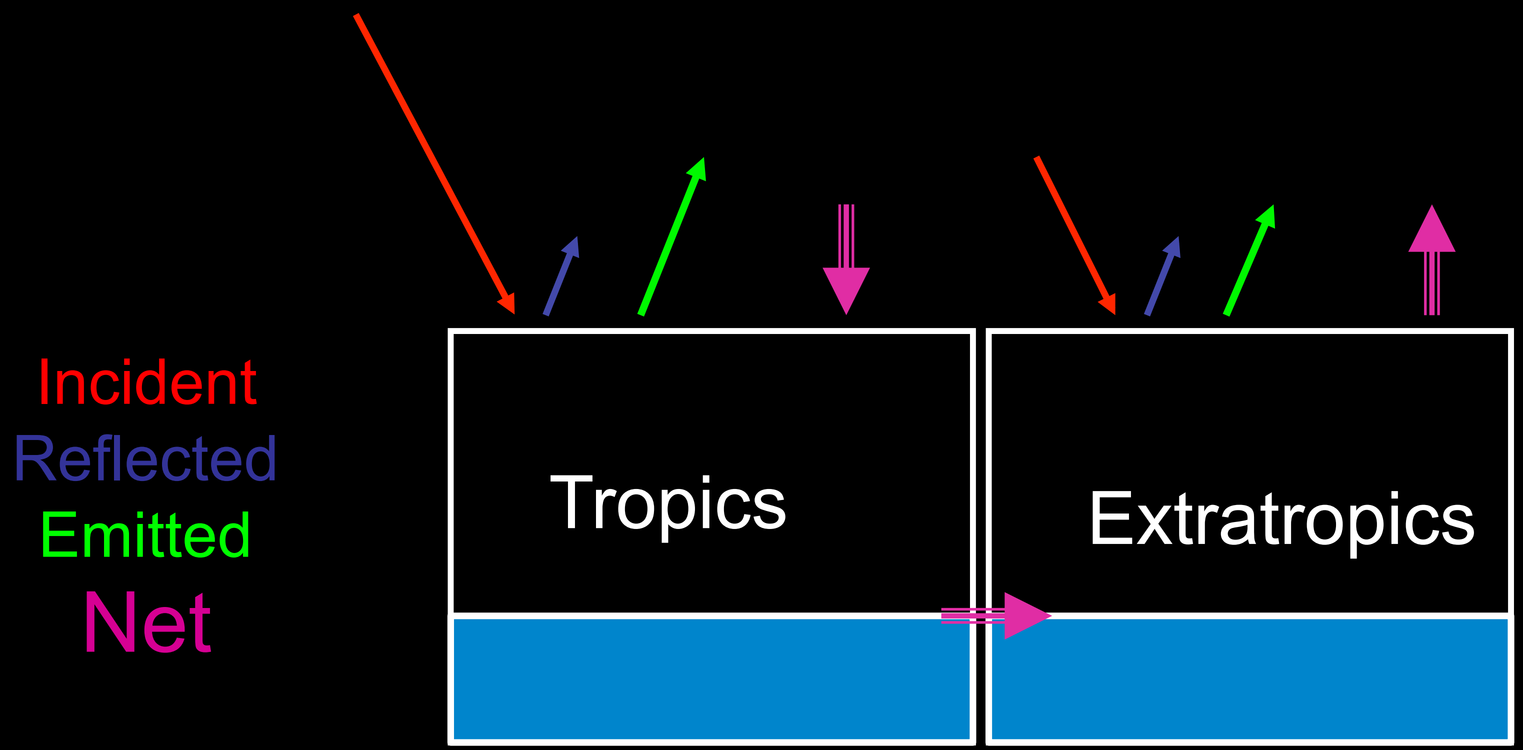


Incident – Reflected = Emitted

$$S(1-\alpha_P) = \sigma T_e^4$$

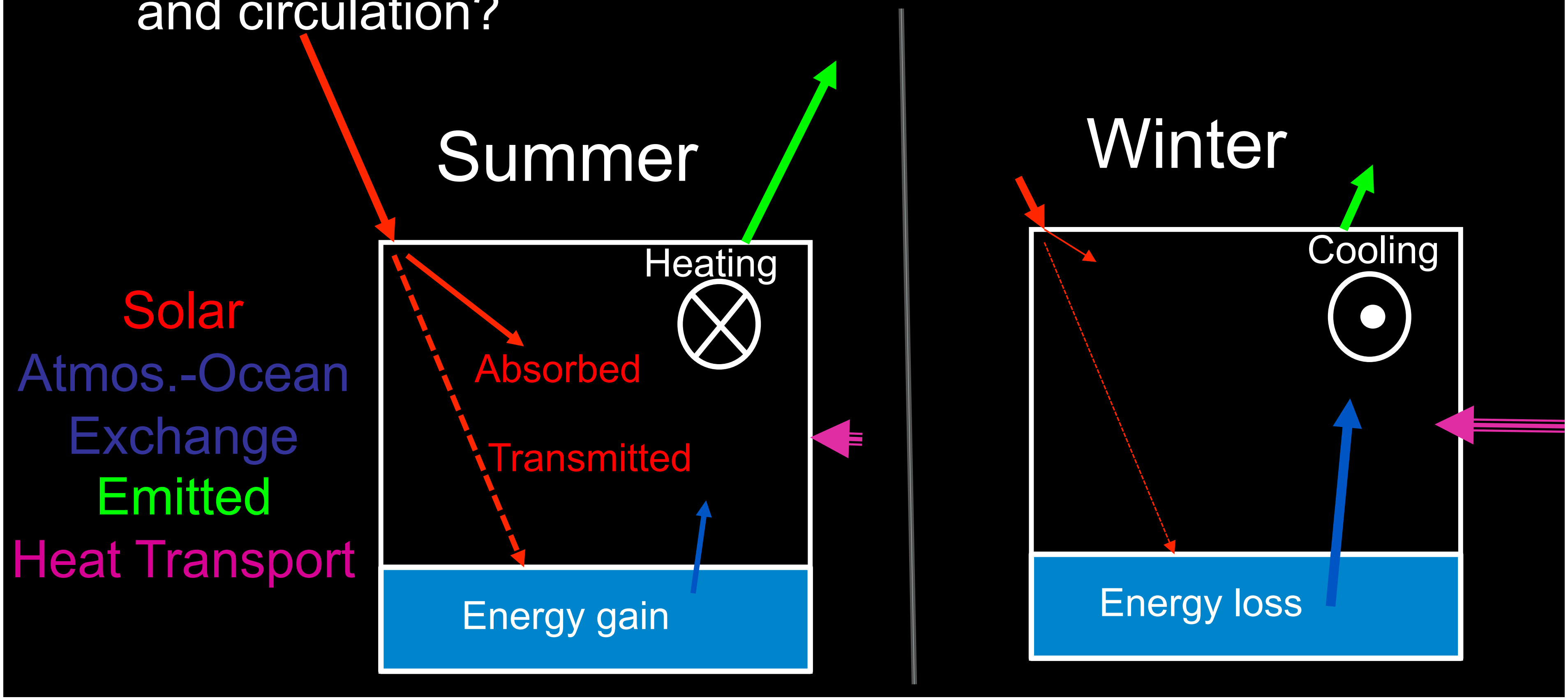
Equator-to-pole contrast

- The tropics receive more solar radiation than the high latitudes (extratropics)
- To come to equilibrium, the tropics must either emit excess radiation or transport energy to the extratropics

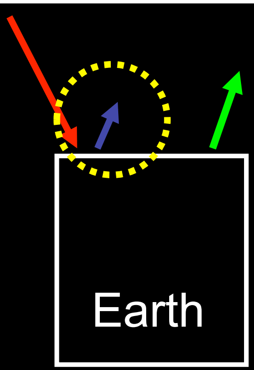


Seasonal Cycle

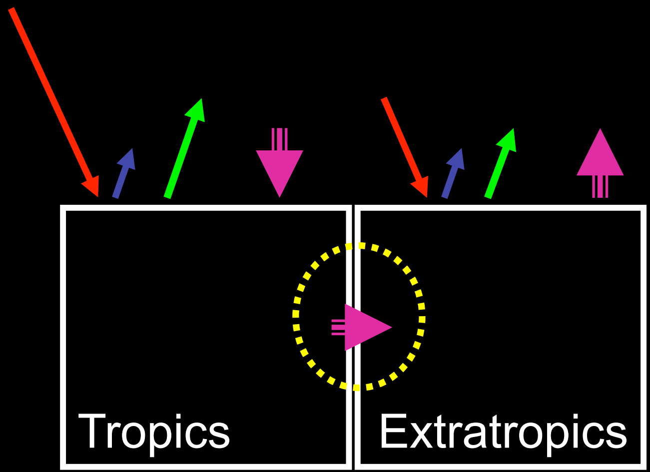
- Seasonal variations in solar insolation are of order 1 in the extratropics
- How much energy goes into the atmosphere versus the ocean to drive seasonal variations in temperature and circulation?



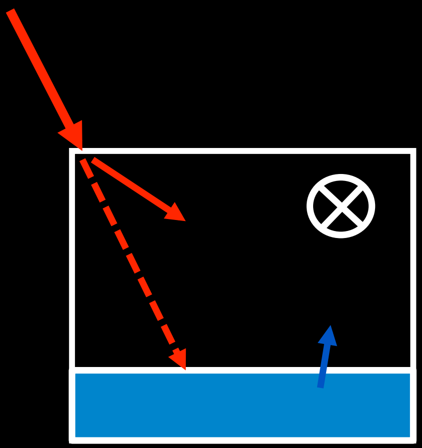
Outline



1. What determines the Earth's planetary albedo? (How much solar radiation gets reflected)

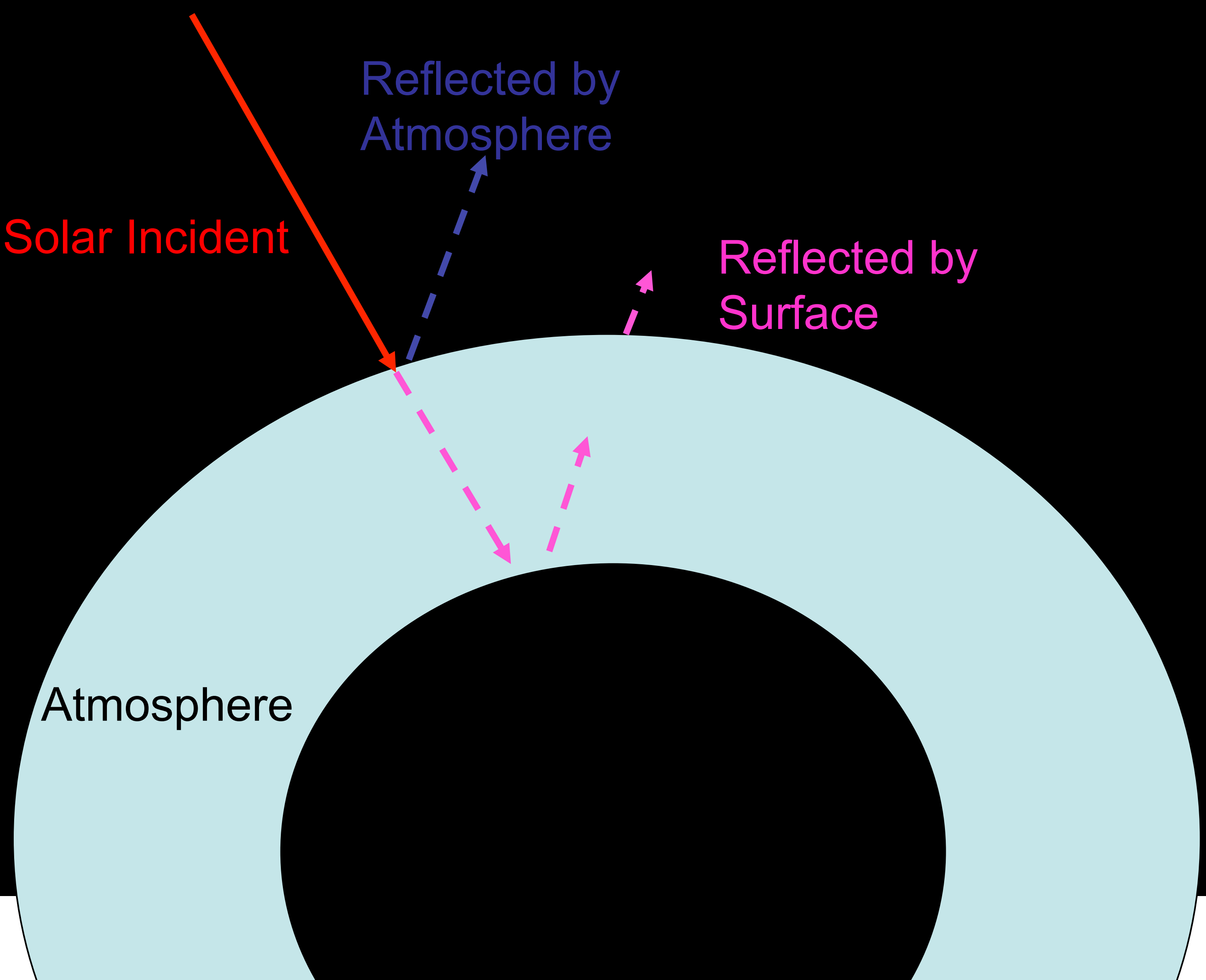


2. What determines the meridional heat transport in the climate system?



3. How do seasonal variations in solar insolation lead to atmospheric heating?

1 : What determines the Earth's planetary albedo?
(solar radiation reflected at top of atmosphere)



Simplified (isotropic) shortwave radiation model

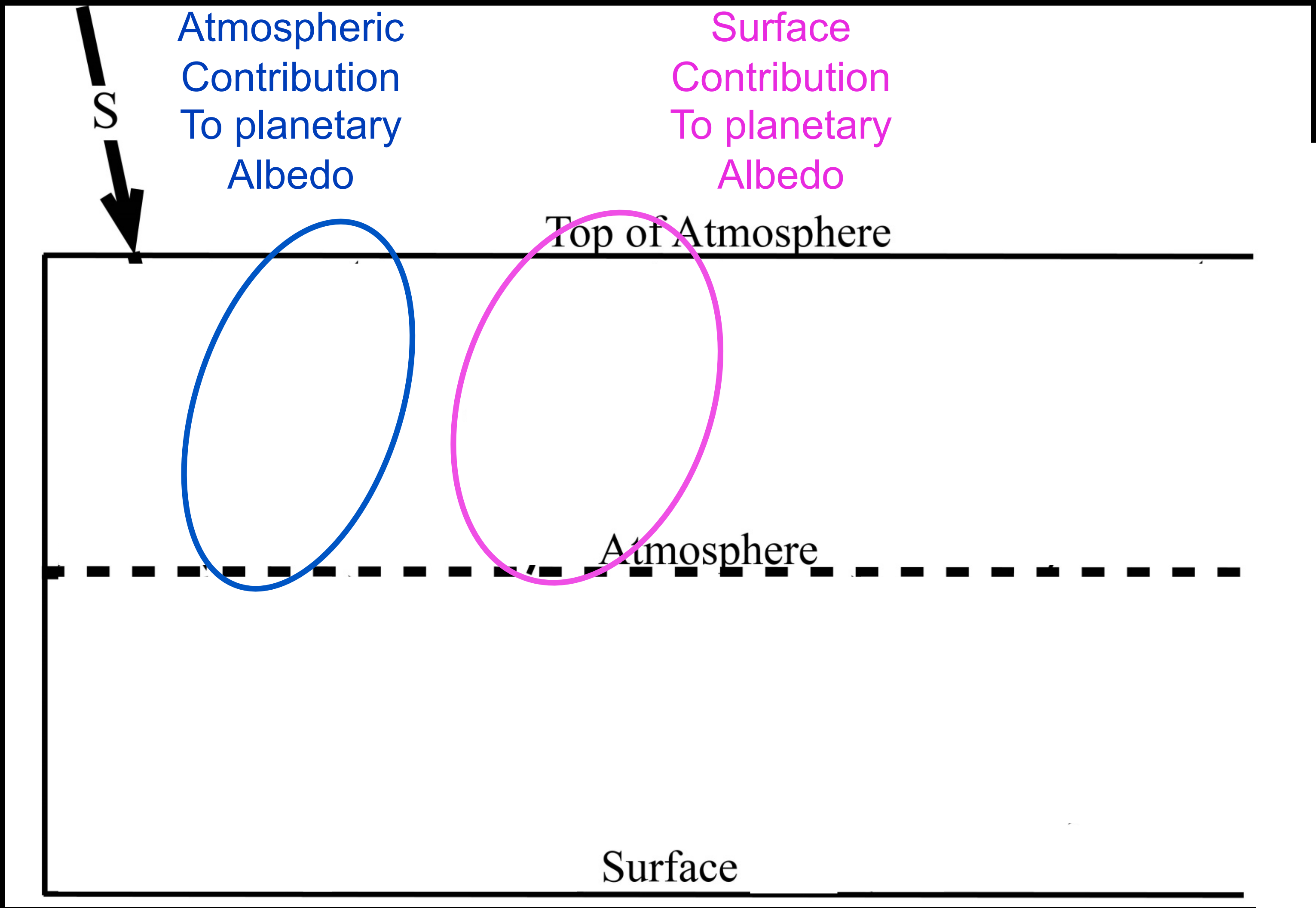
S = incident

R = cloud reflection

A = absorption

α = surface albedo

(UNKNOWNS)

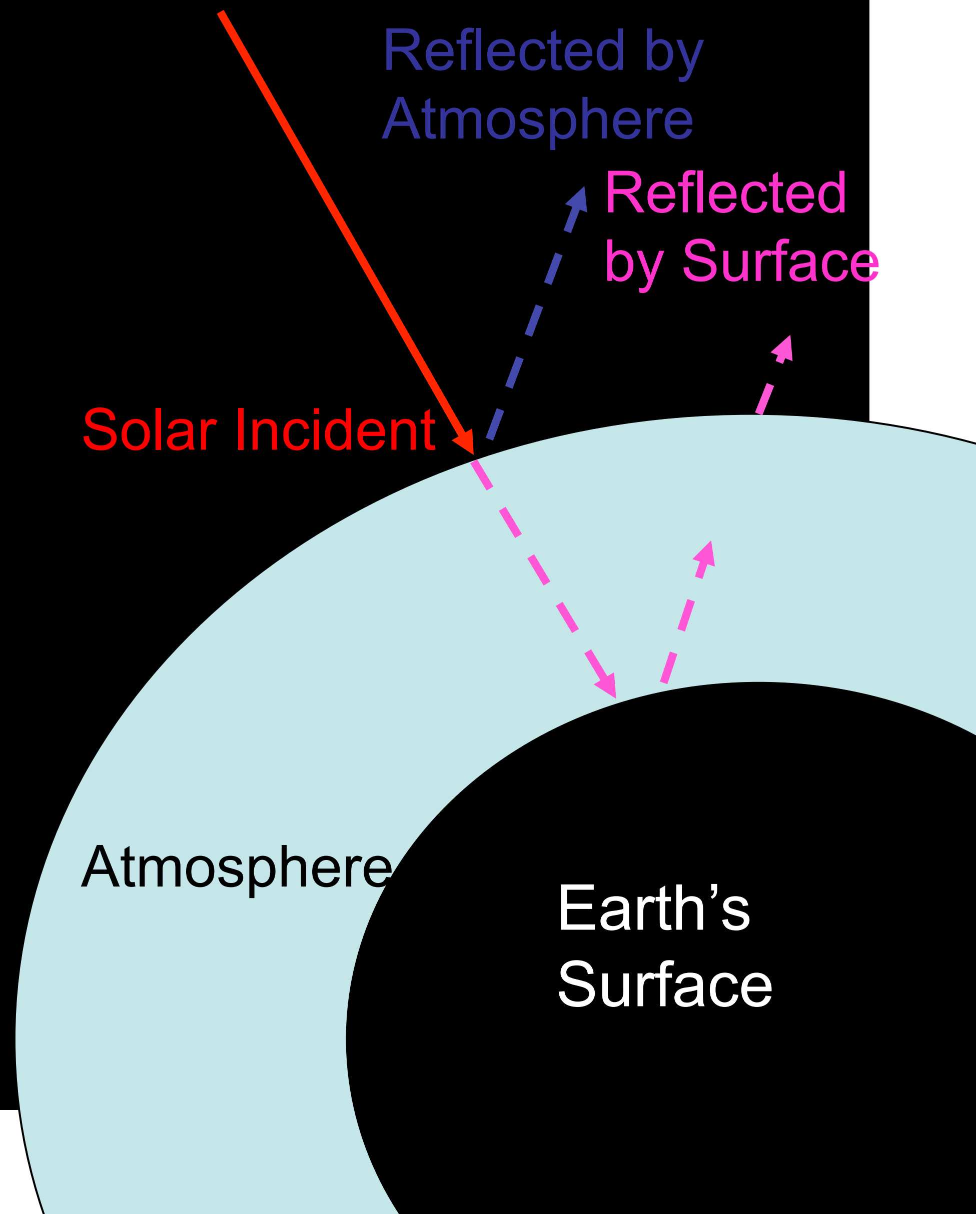


Partitioning of planetary albedo into atmospheric and surface components

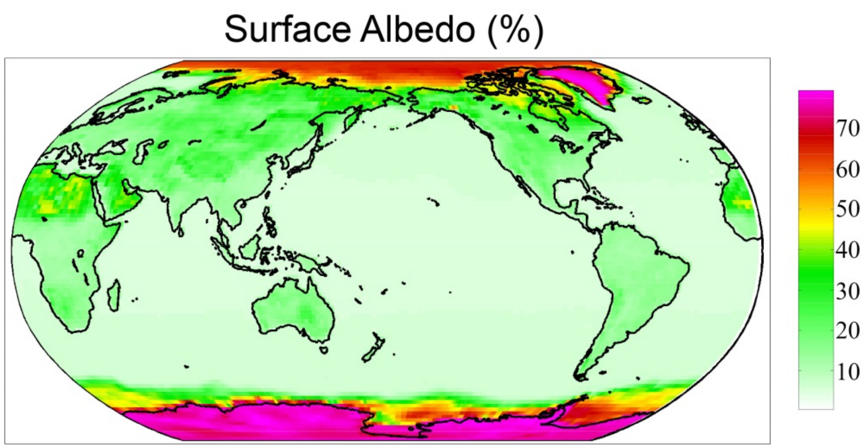
$$\alpha_P = \alpha_{P,ATMOS} + \alpha_{P,SURF}$$

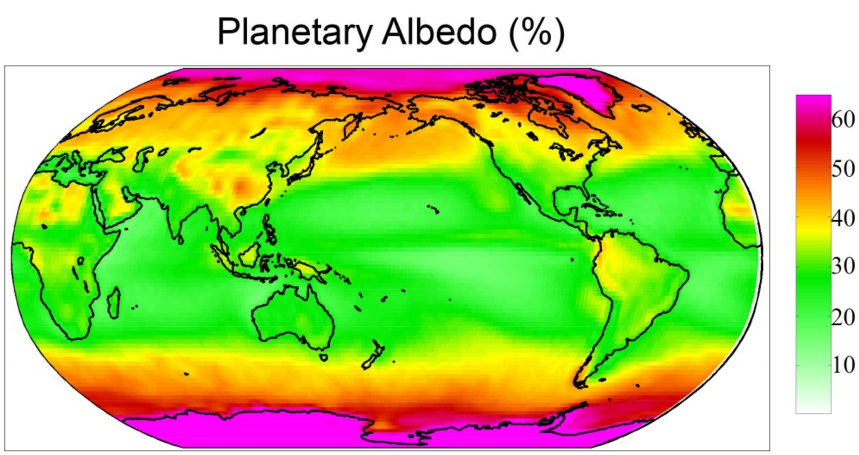
$$\alpha_{P,ATMOS} = R$$

$$\alpha_{P,SURF} = \frac{\alpha(1-R-A)^2}{(1-\alpha R)}$$

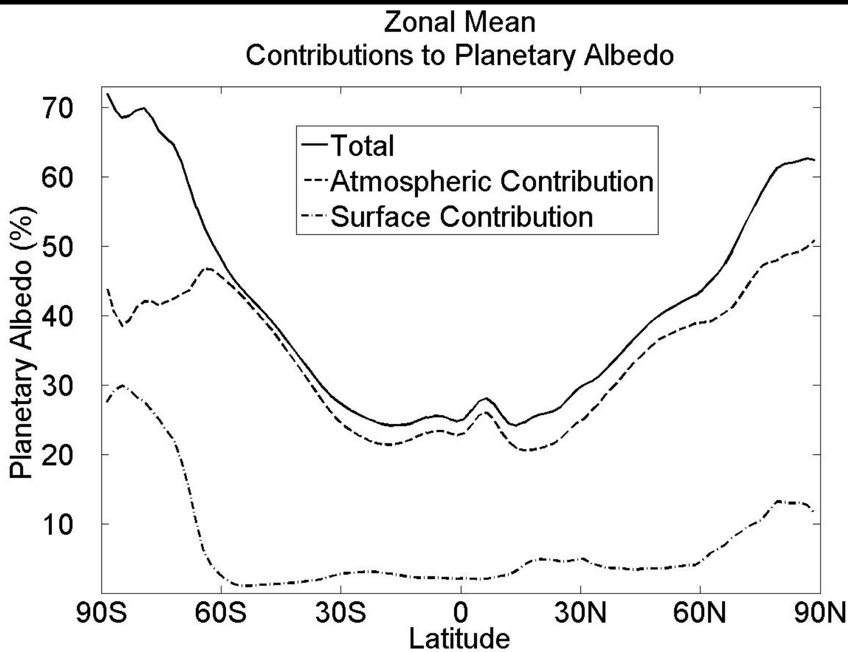


Observed (CERES) surface and atmospheric contribution to planetary albedo





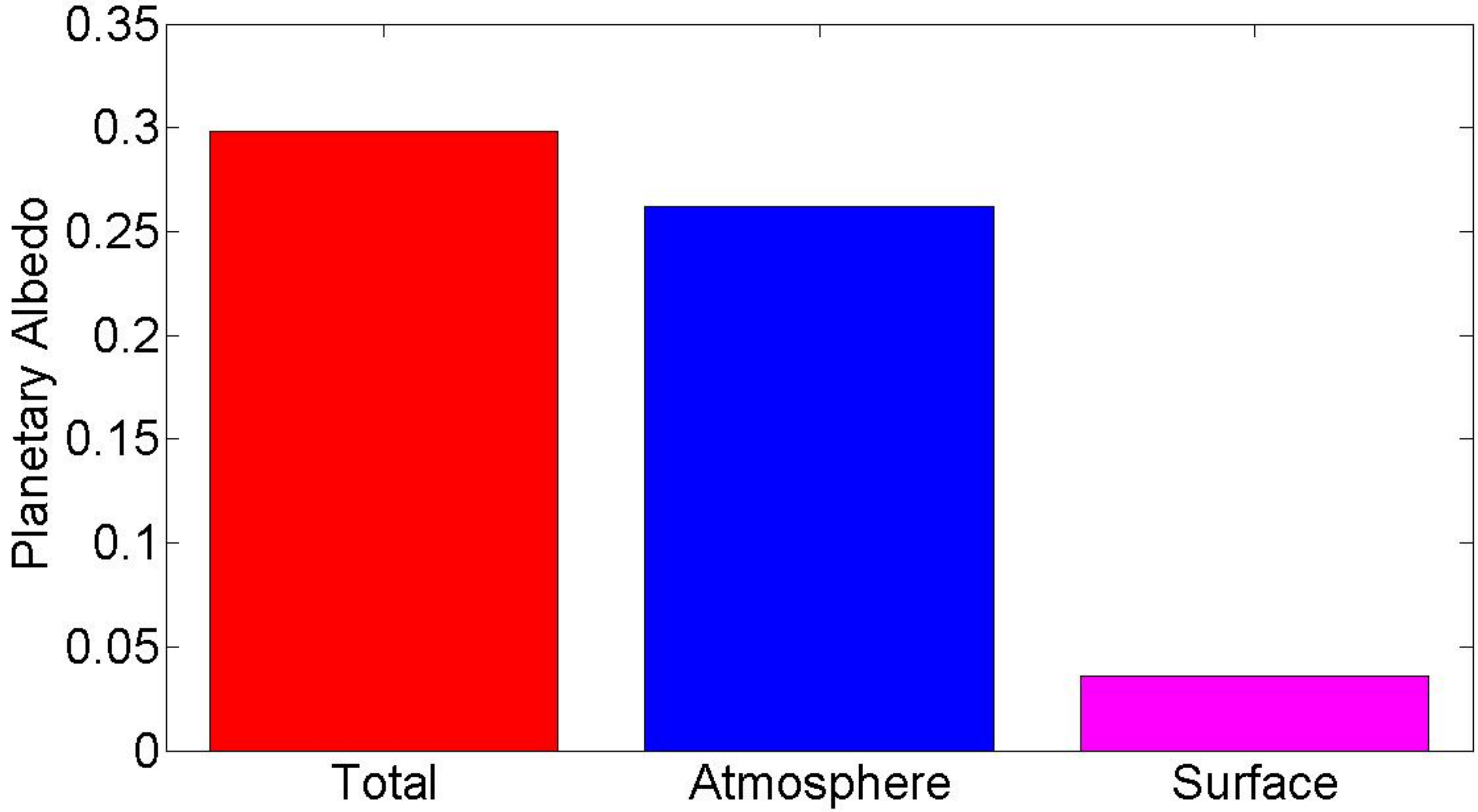
Observed Surface and atmospheric contribution to planetary albedo



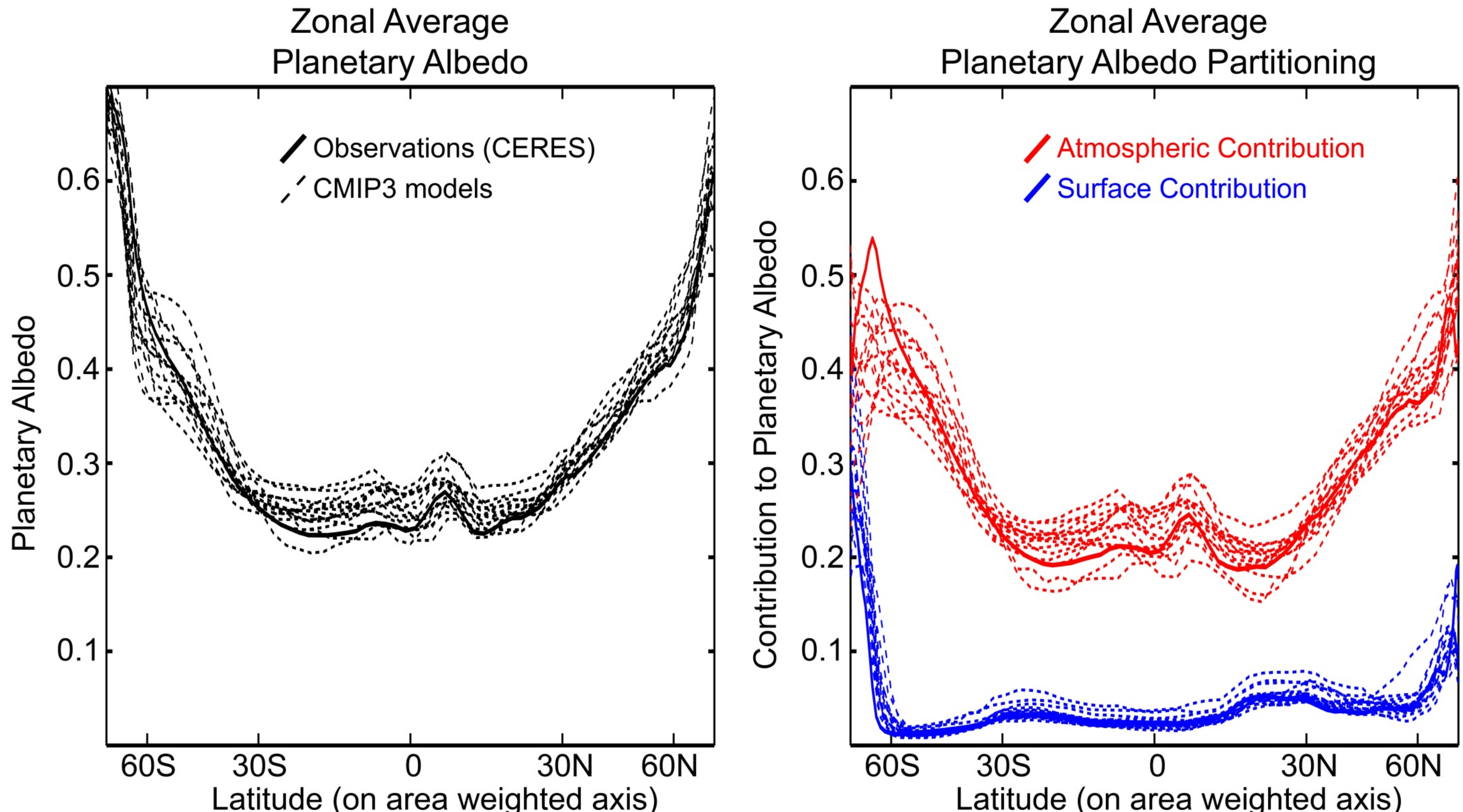
Surface albedo and surface contribution to planetary albedo (α and $\alpha_{P,SURF}$)

$$\alpha_{P,SURF} = \frac{\alpha(1-R-A)^2}{(1-\alpha R)}$$

Observed Global Mean Planetary Albedo and it atmospheric/surface Partitioning



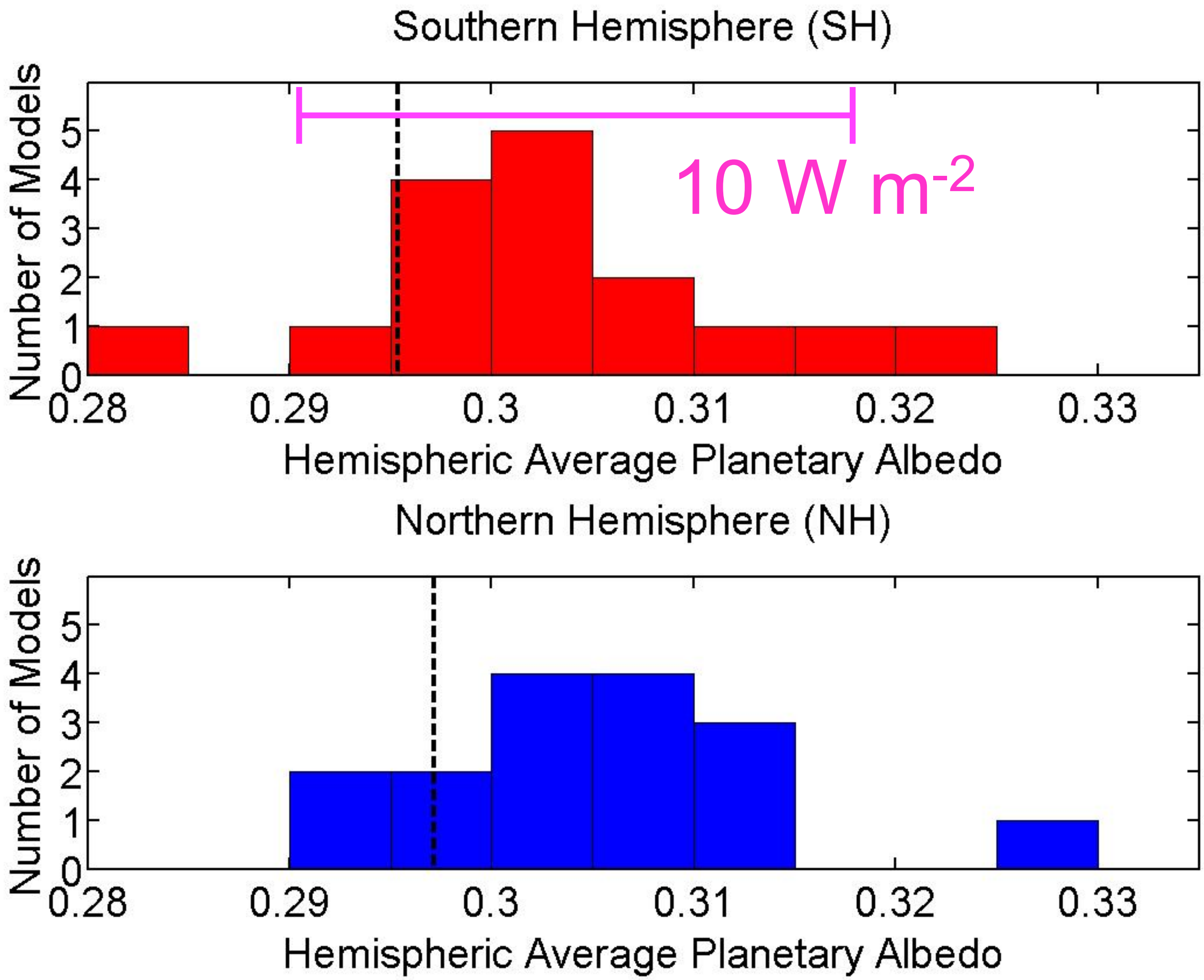
Planetary Albedo Partitioning: Comparison of models (CMIP3 pre-industrial) and observations (CERES)



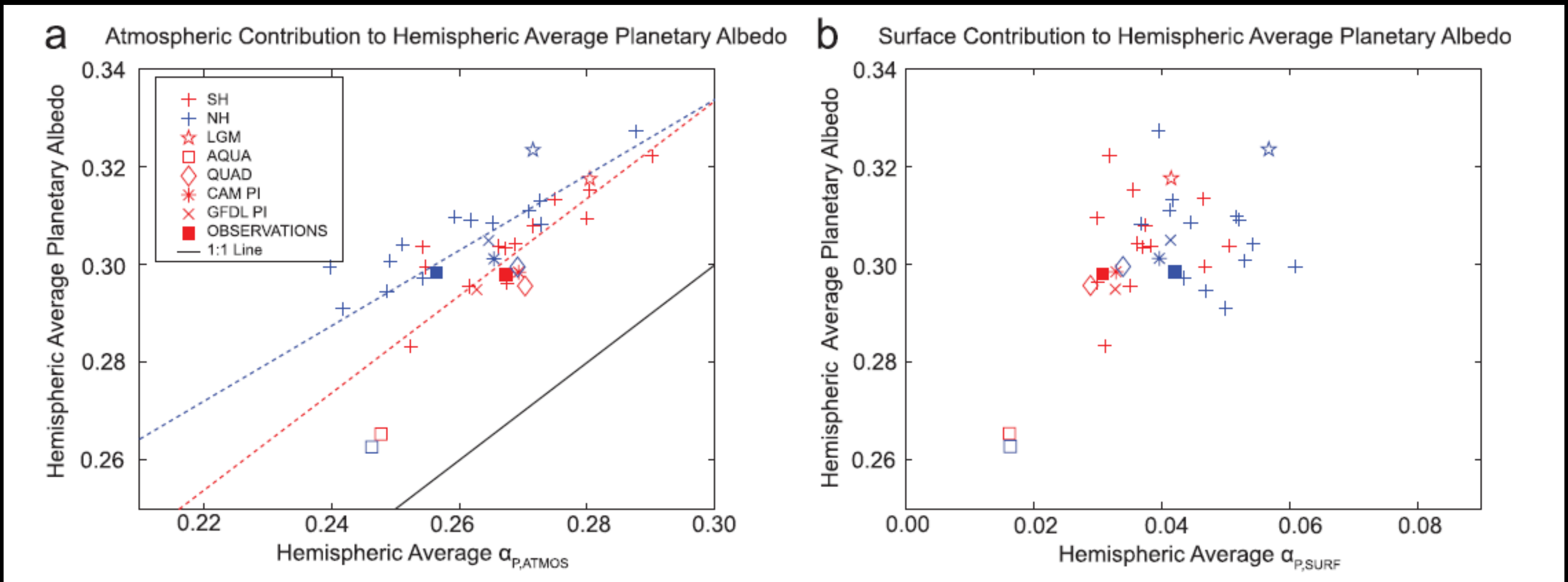
Histogram of hemispheric average planetary albedo

Observations

(CERES)

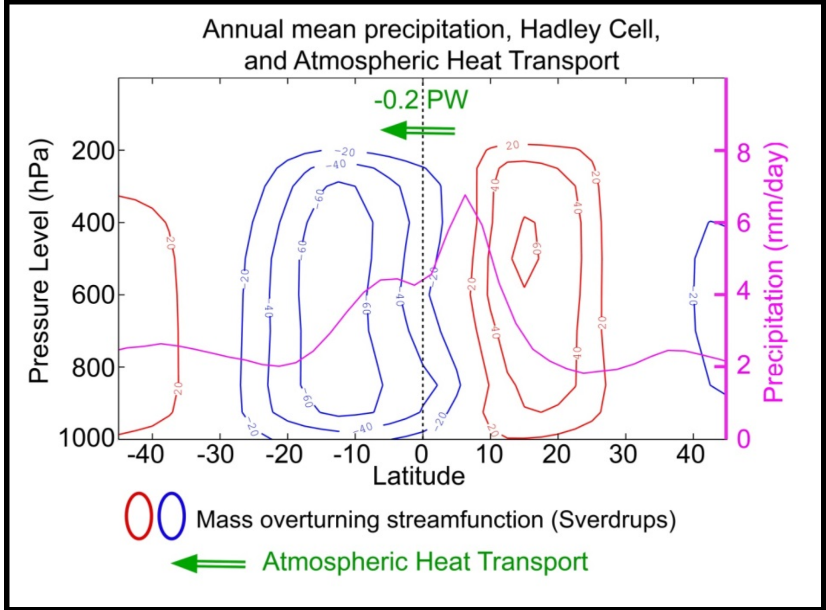


Hemispheric average planetary albedo partitioning in climate models



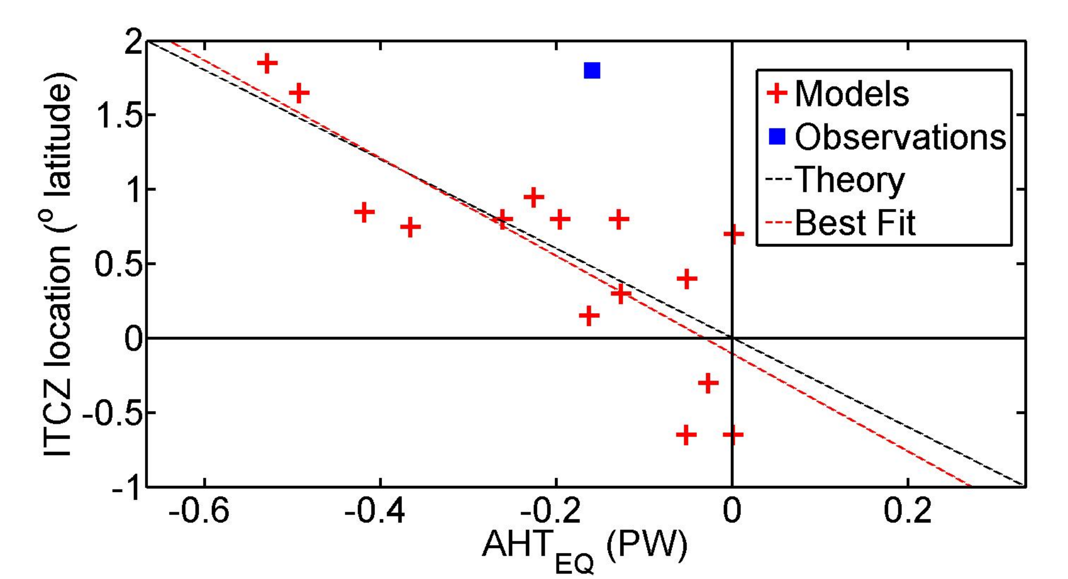
- Inter-model spread in Hemispheric average planetary albedo is a consequence of differences in cloud reflection
- Surface albedo makes a much smaller contribution to basic state albedo, model bias and inter-model spread

Inter-hemispheric energy transport and the location of tropical precipitation

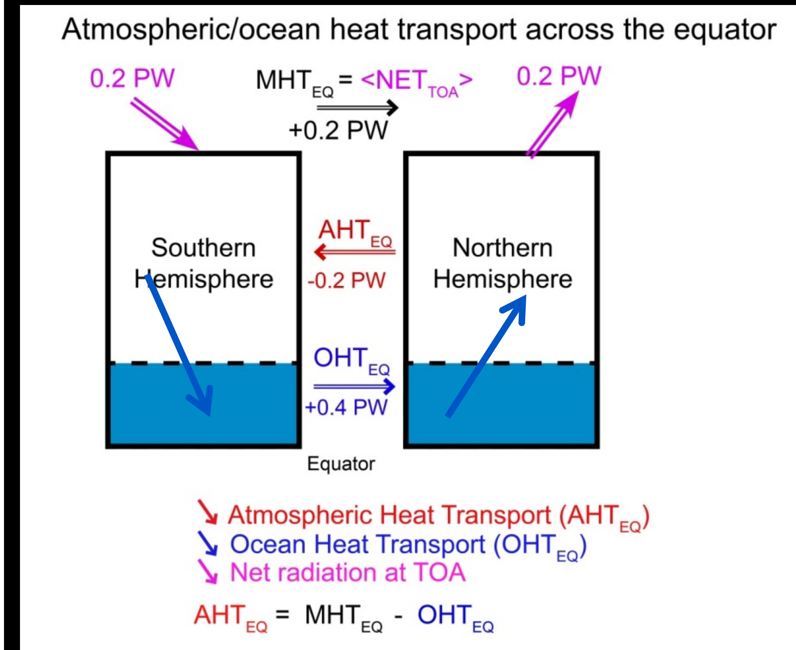


ITCZ location and atmospheric heat transport across the equator (AHT_{EQ})are both a consequence of the Hadley cell location
-> The atmosphere moves energy away from the ITCZ

The inter-model spread in AHT_{EQ} and ITCZ location are strongly correlated

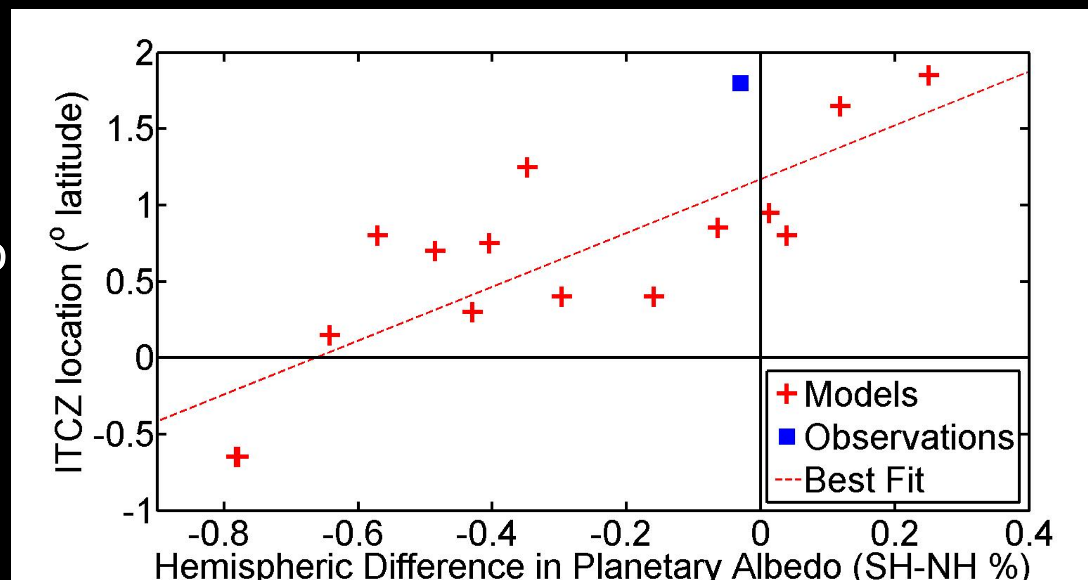


Hemispheric contrast of radiation and ITCZ location



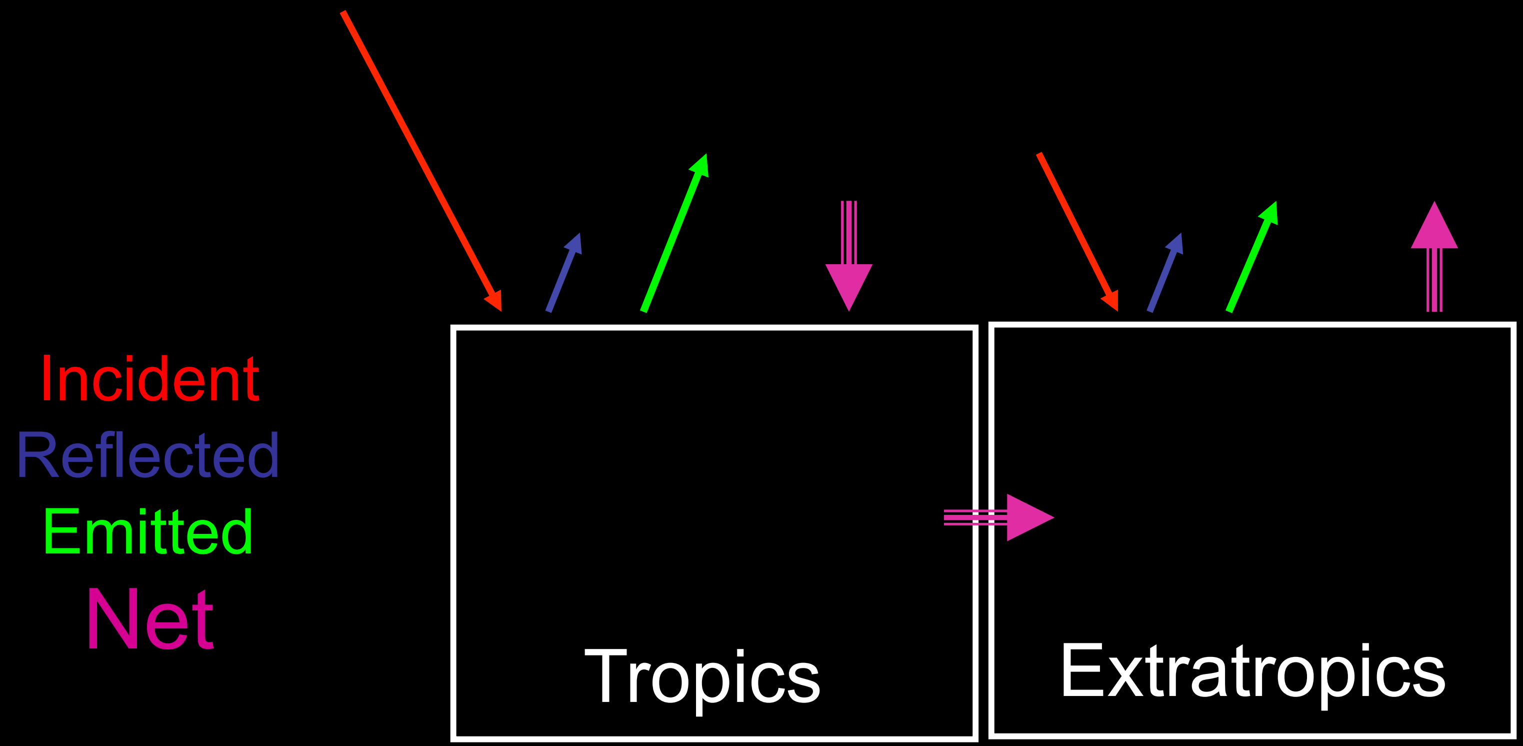
ITCZ lives in the hemisphere where the atmosphere is heated more strongly
-> In observations, the radiative input to each hemisphere is nearly equal and ITCZ is North of the equator because of Northward ocean heat transport

Model biases is planetary albedo lead to ITCZ biases
-> SH absorbs too much shortwave and ITCZ is too far south

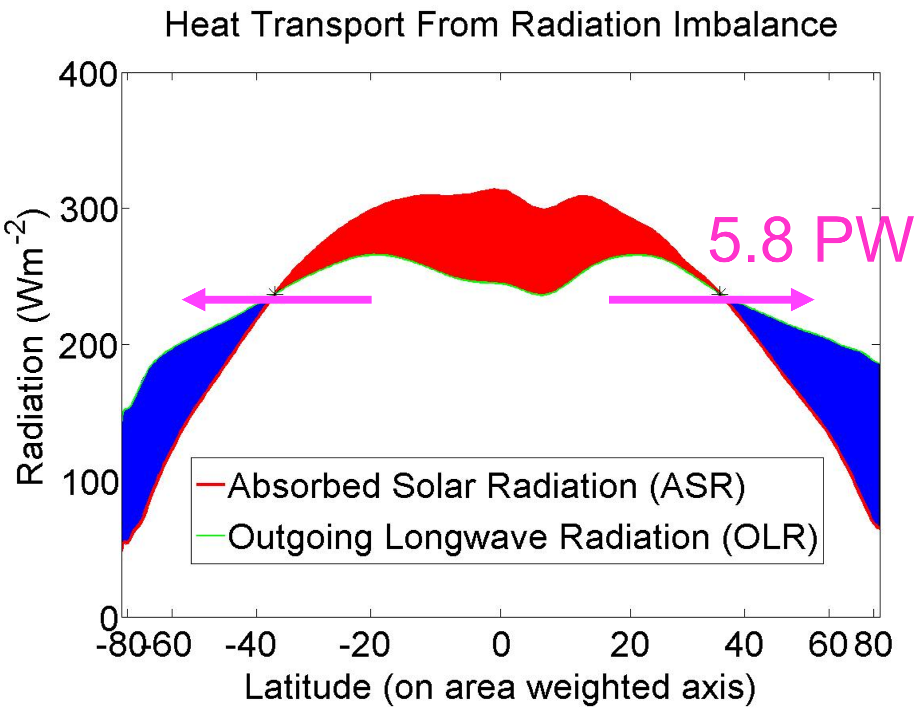


Heating of SH

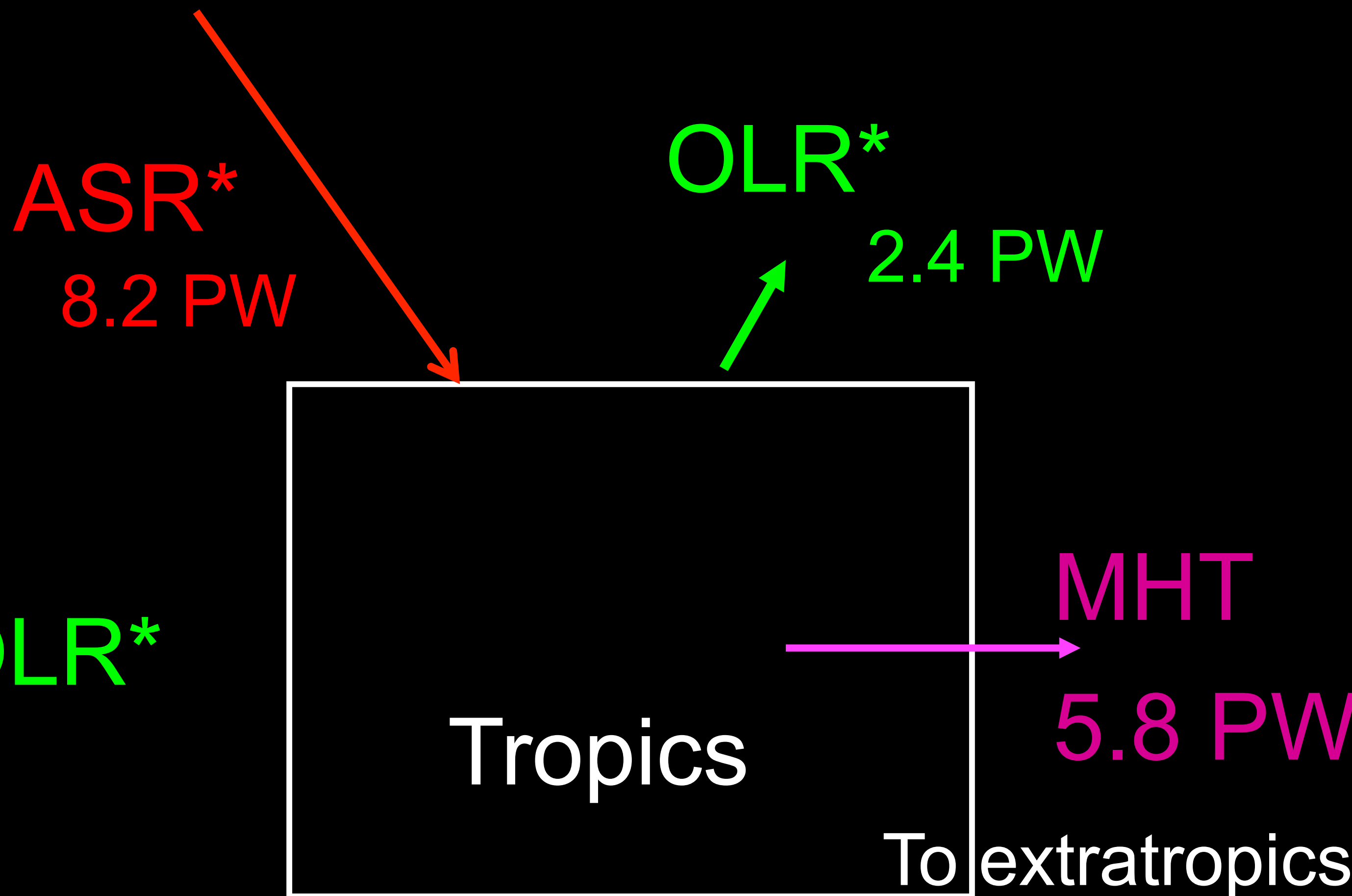
2 : What determines meridional heat transport?



Understanding heat transport



ASR*, OLR*, MHT, and the tropical/ extratropical energy budget



MHT =

ASR* - OLR*

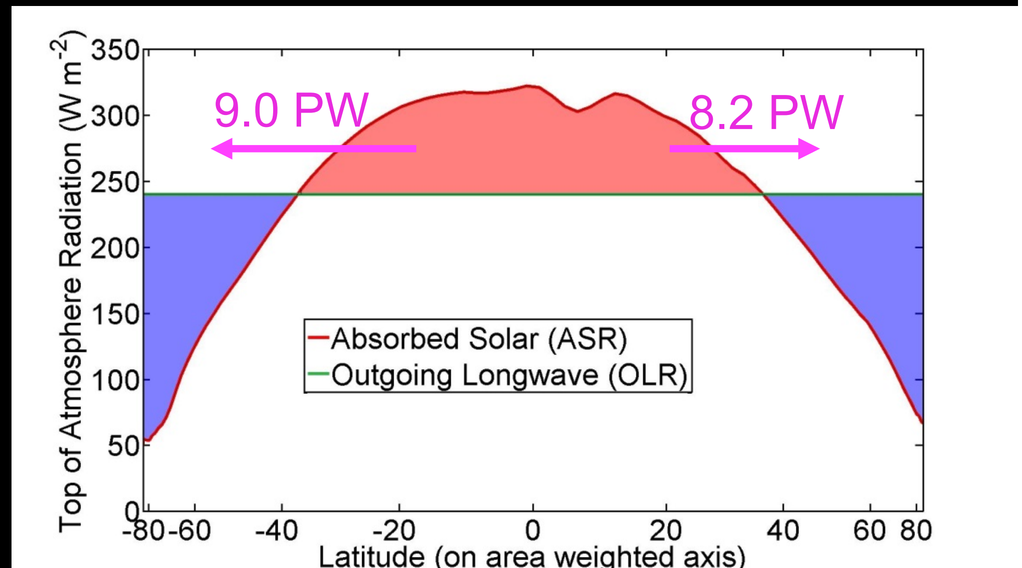
All arrows are relative to the global average

ASR*, OLR*, MHT Dynamic Limit

MHT = ASR*

OLR* = 0

ASR*
8.2 PW



MHT
8.2 PW

Tropics

To extratropics

All arrows are relative to the global average

ASR*, OLR*, MHT
Radiative Limit

MHT = 0 ,

ASR* = OLR*

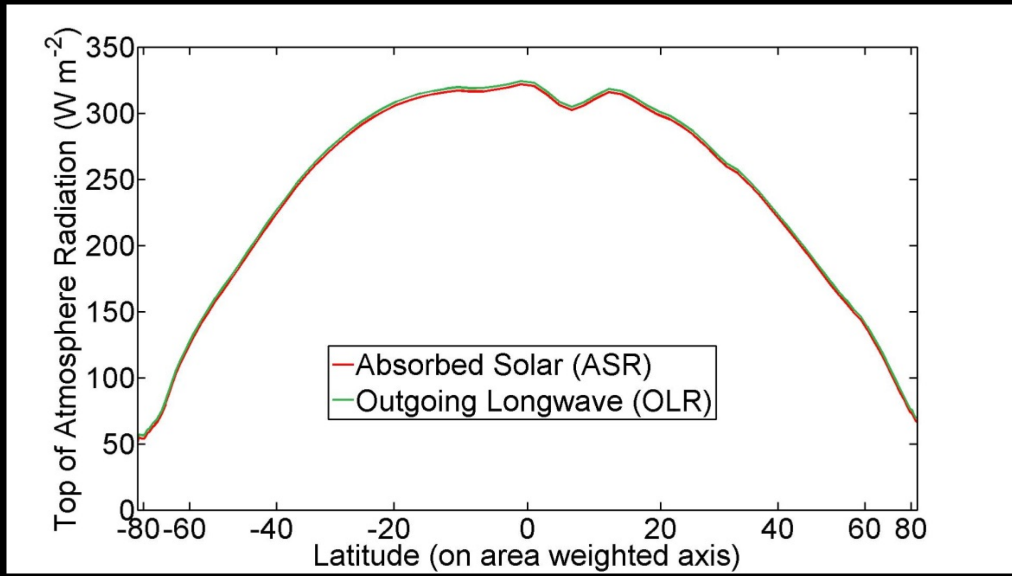
ASR*
8.2 PW

OLR*
8.2 PW

MHT
0 PW

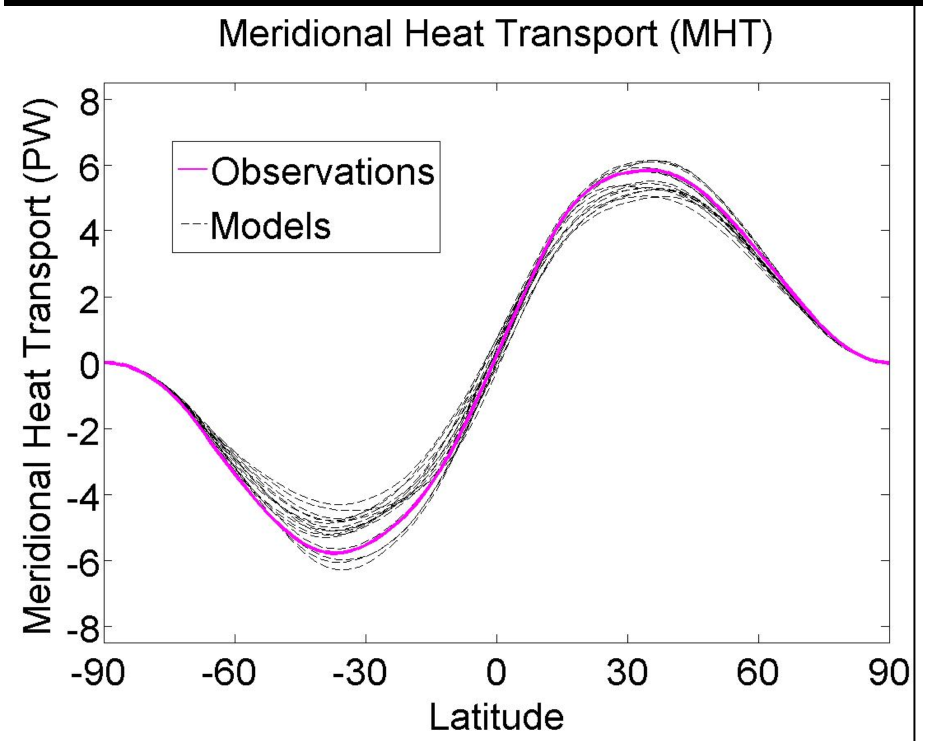
Tropics

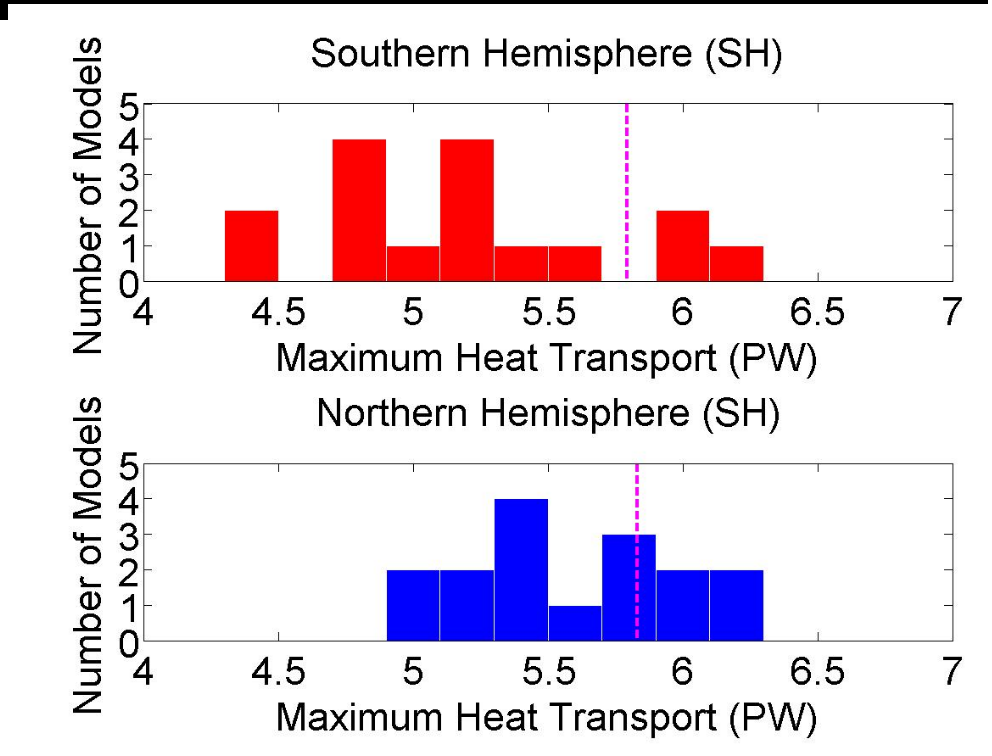
To extratropics



All arrows are relative to the global average

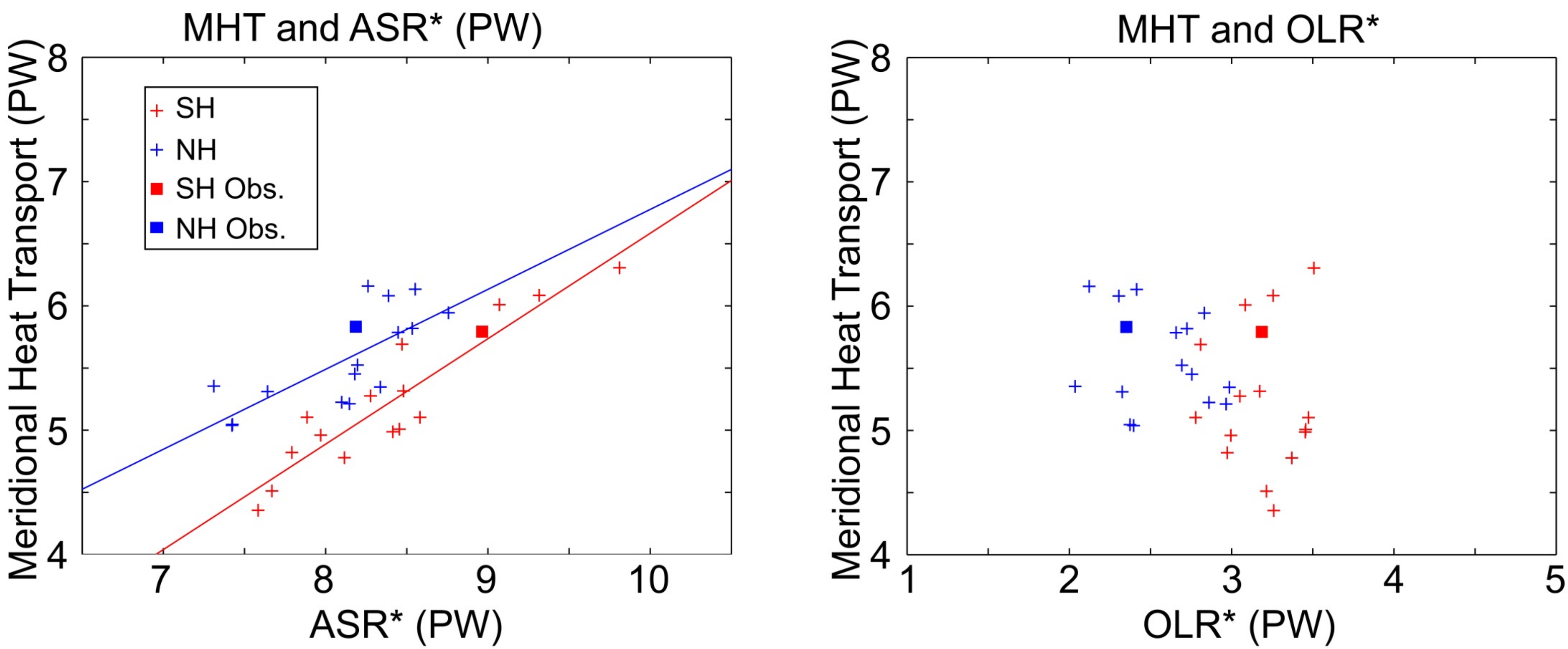
Heat Transport In Climate Models (CMIP3)



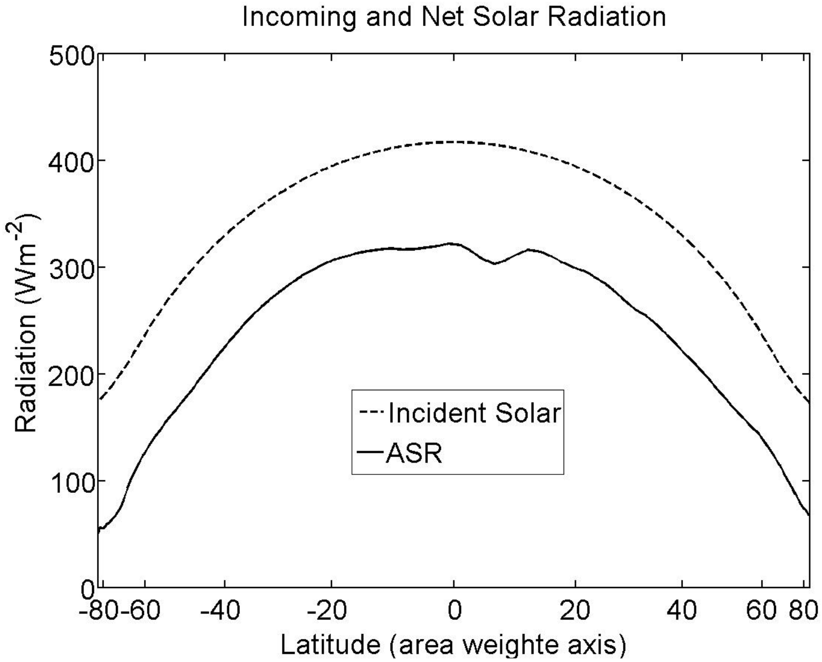


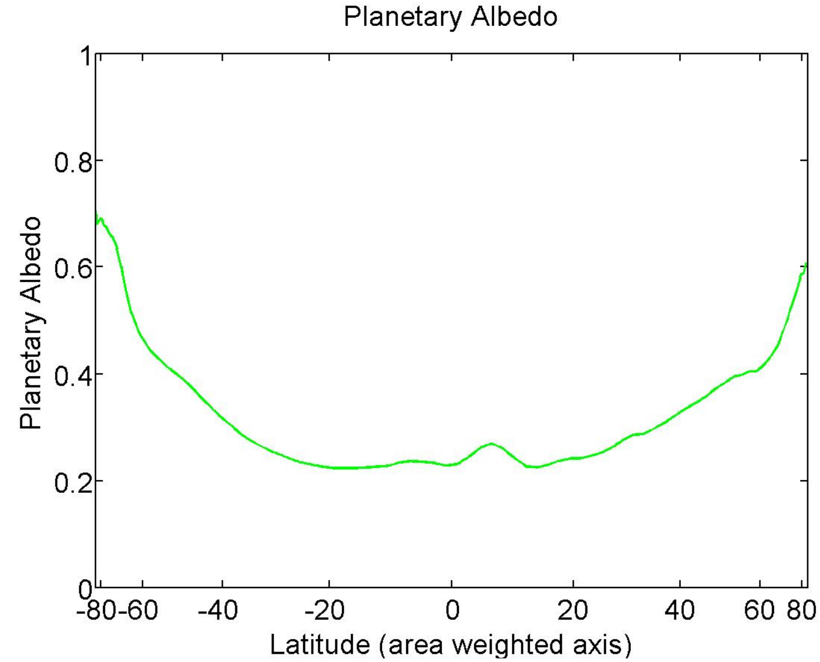
- - - Observations

Model heat transport spread in terms of OLR* and ASR*

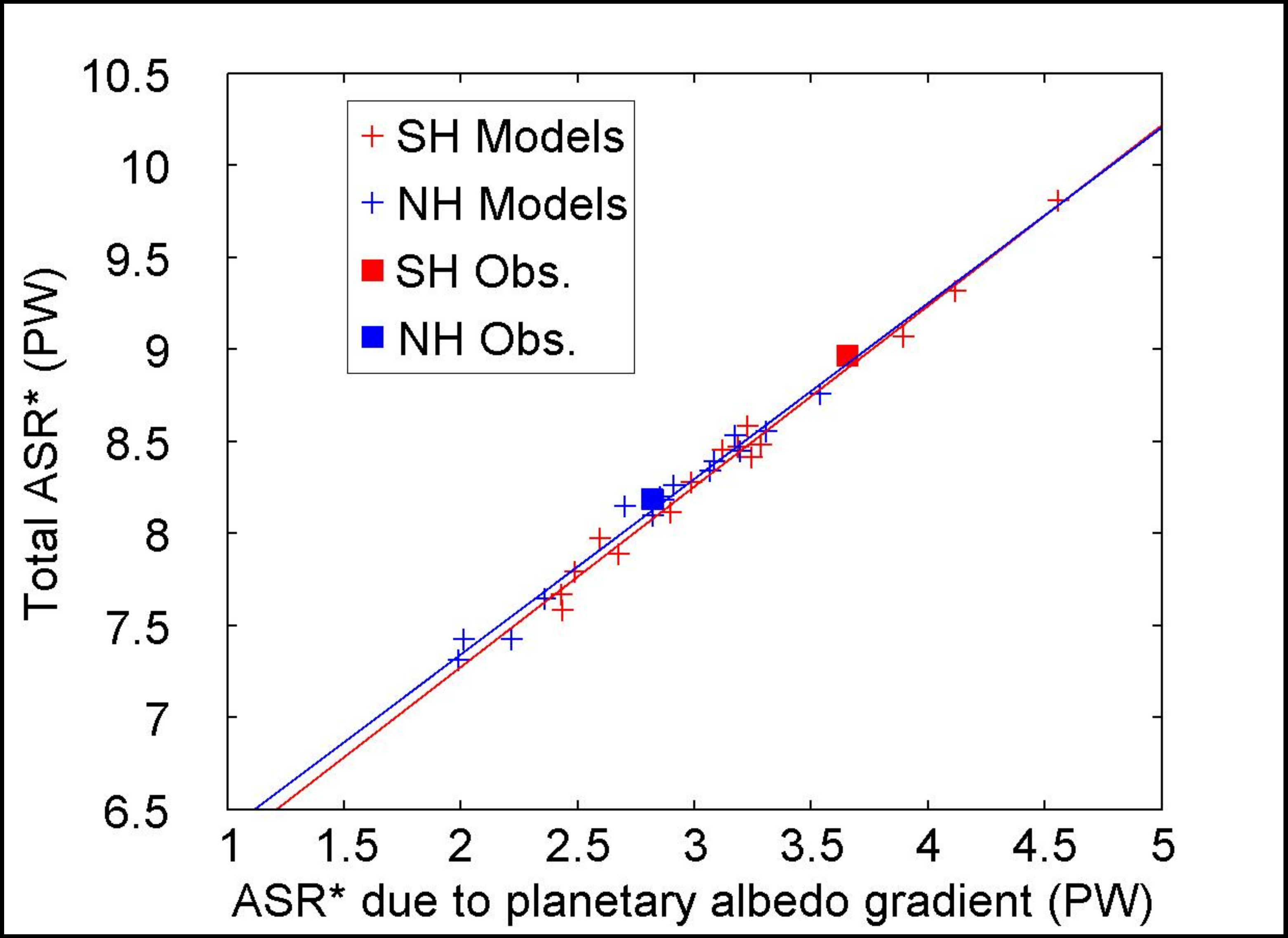


Understanding ASR*

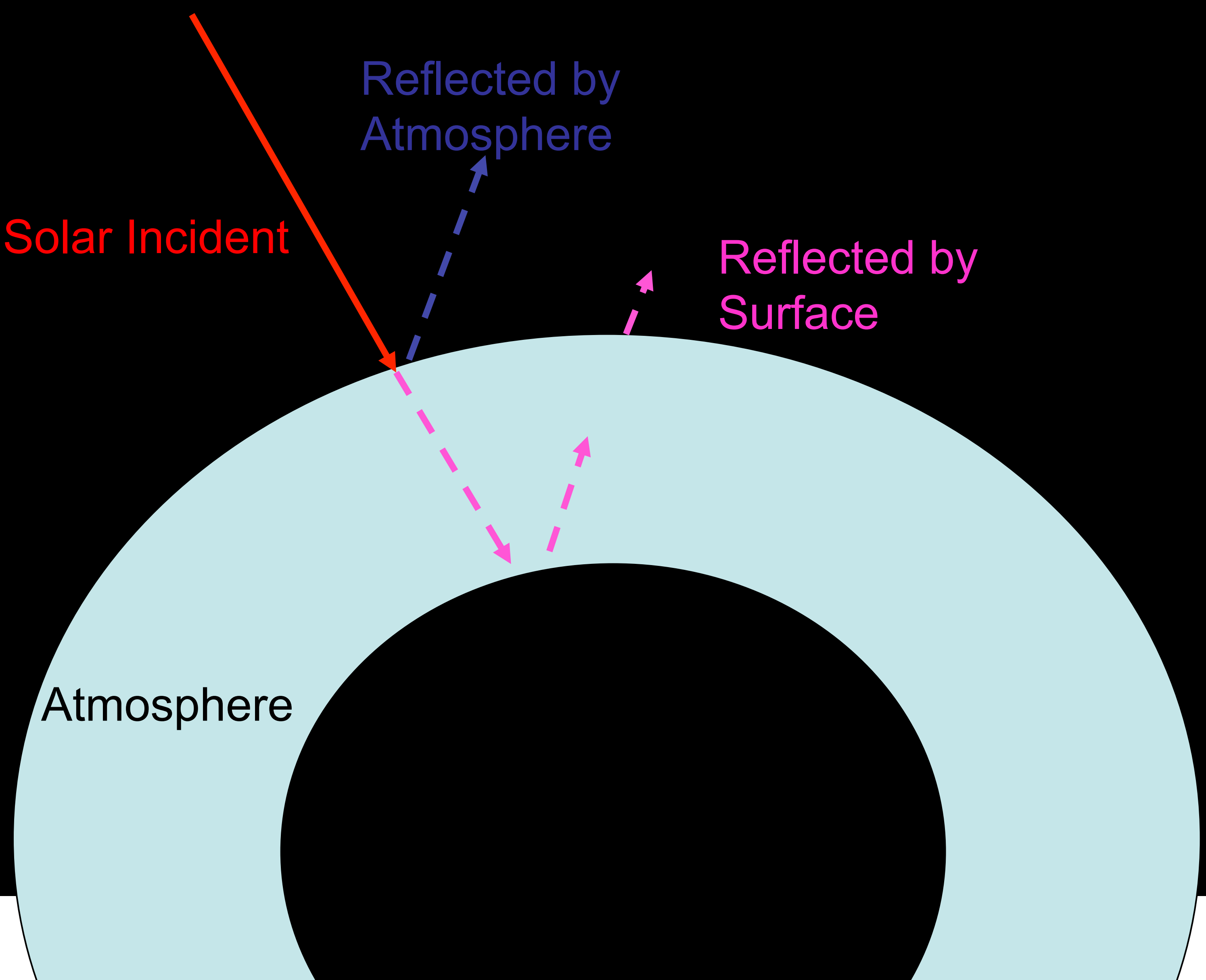




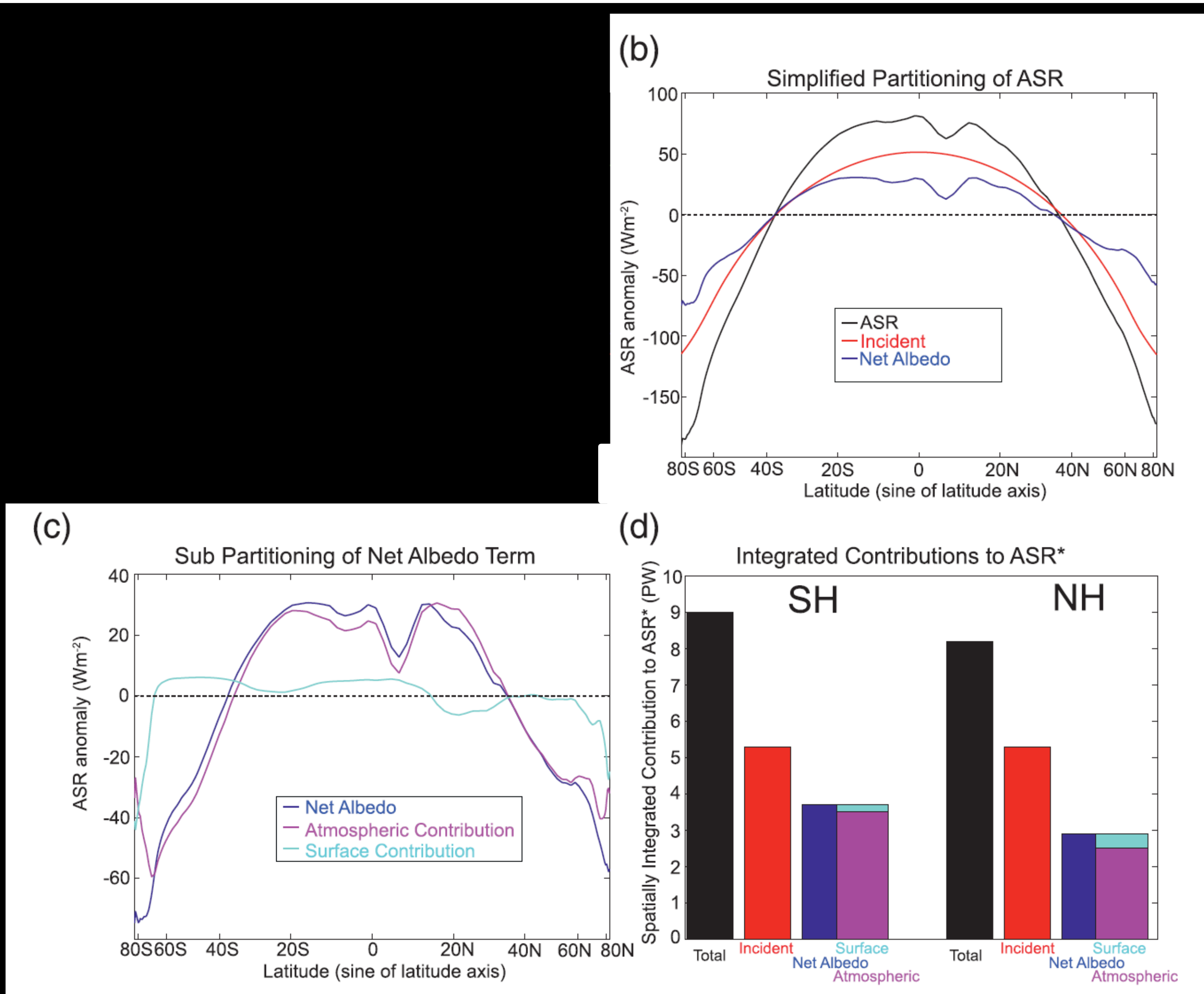
ASR* and planetary albedo



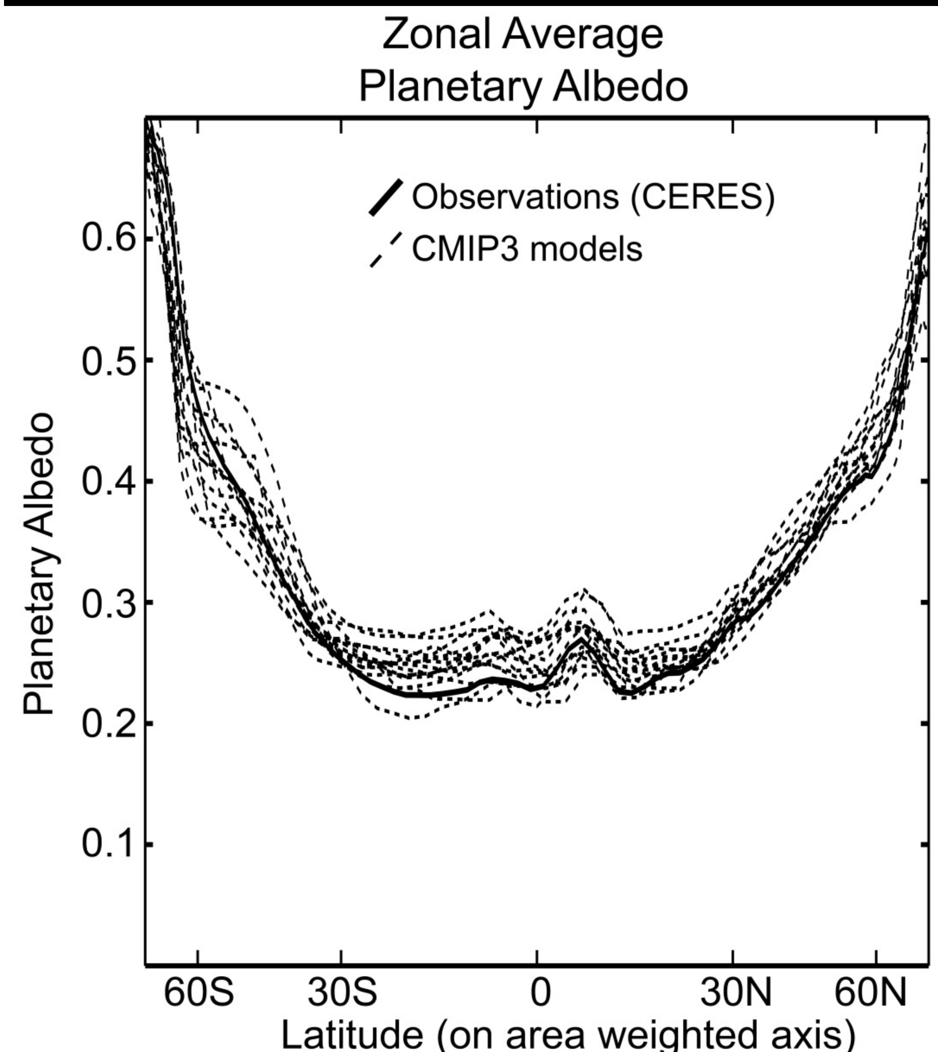
What determines the equator-to-pole contrast of planetary albedo?

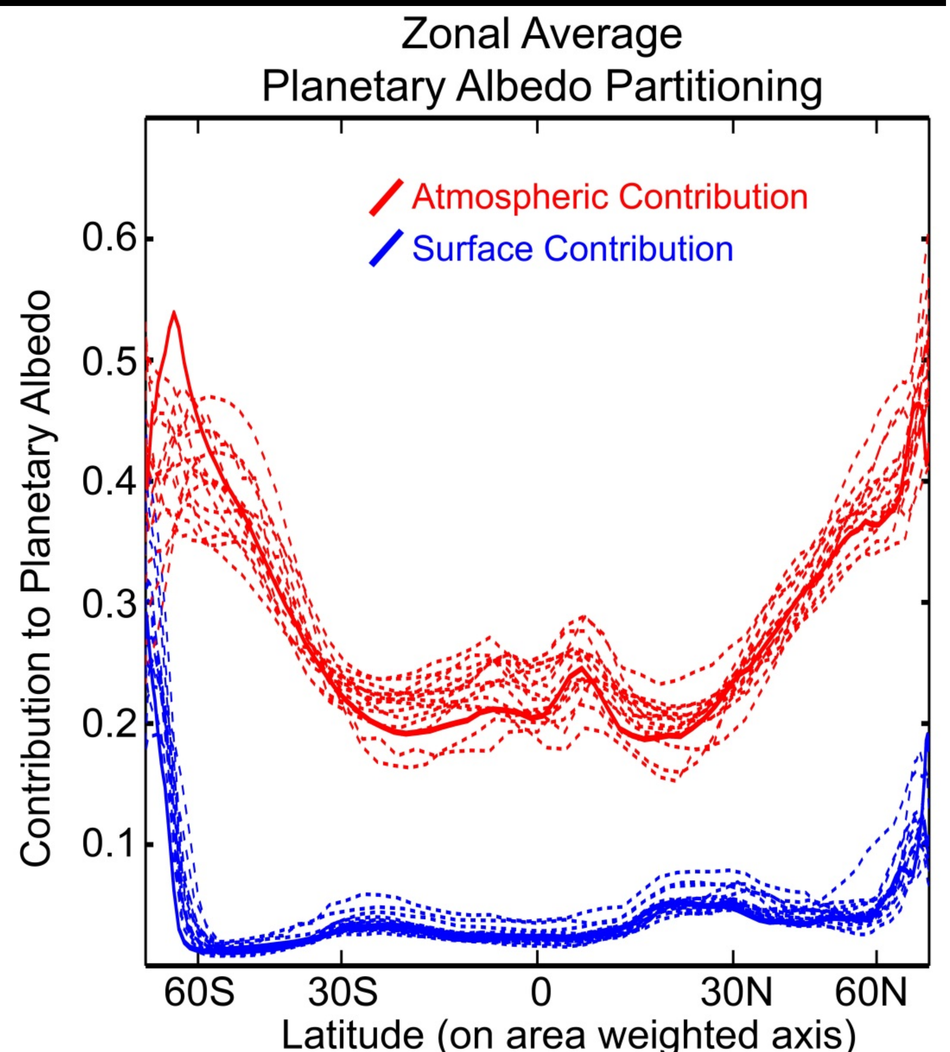


Surface and atmospheric contributions to the equator-to-pole contrast in absorbed shortwave radiation



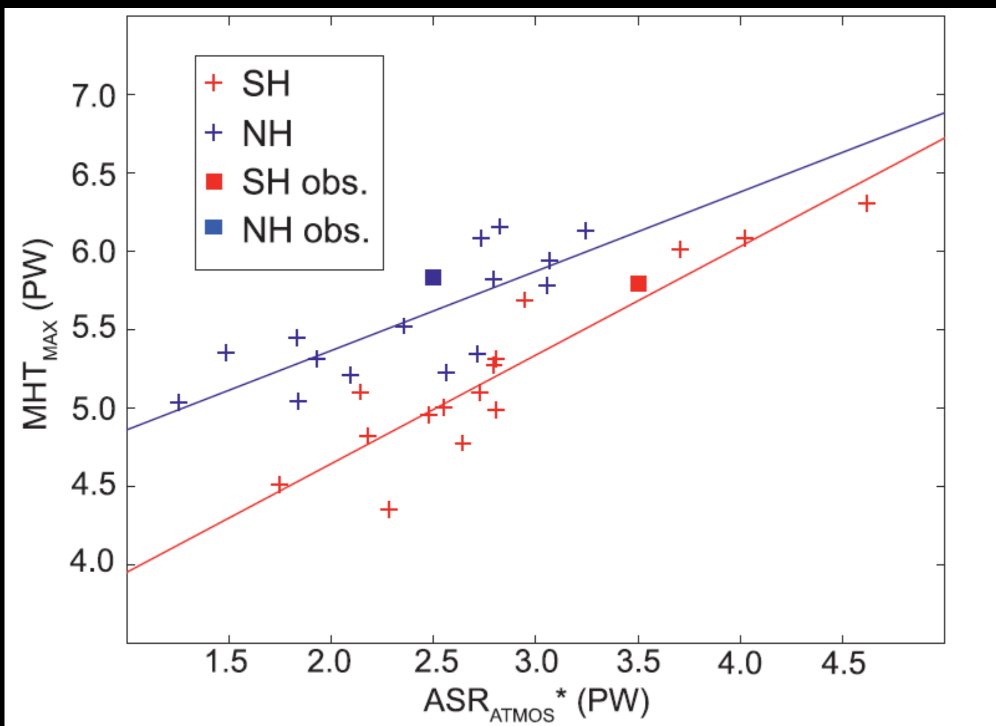
Planetary Albedo Partitioning





Atmospheric and Surface reflection contribution to ASR*

Poleward Energy Transport



Equator to pole contrast in clouds

Cloud Reflection

⇓

Equator to pole contrast of absorbed shortwave

⇓

Poleward Energy Transport

3. The seasonal cycle of atmospheric heating and temperature

30% reflected

20% absorbed atmosphere

50% transmitted
To surface

50% net flux
From surface
To
atmosphere

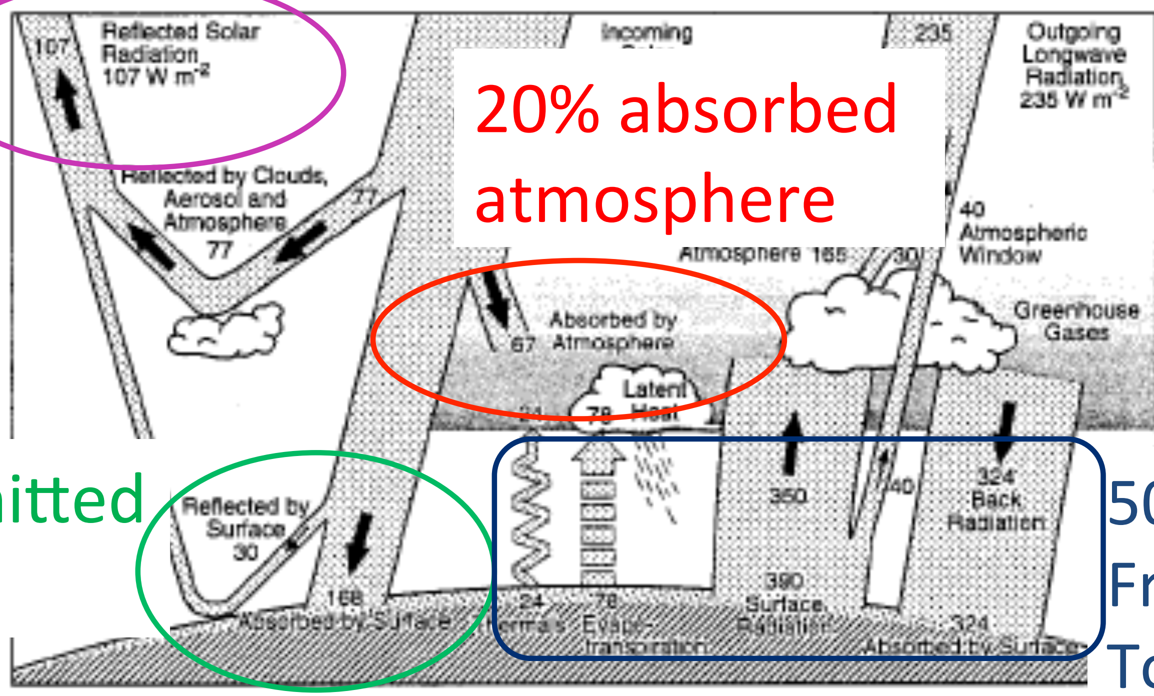
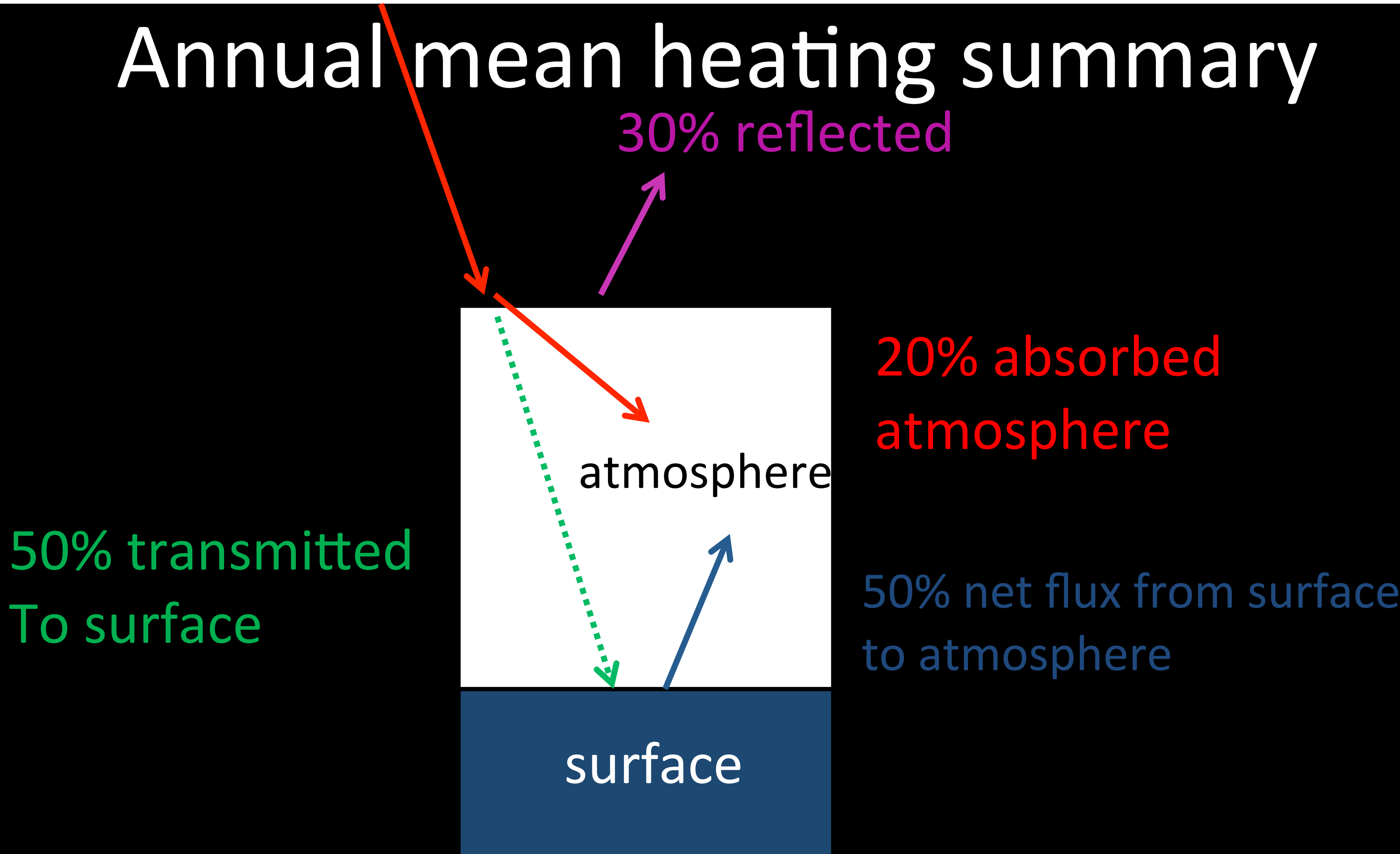


FIG. 7. The earth's annual global mean energy budget based on the present study. Units are W m^{-2}.

Kiehl and Trenberth 1997

Annual mean heating summary

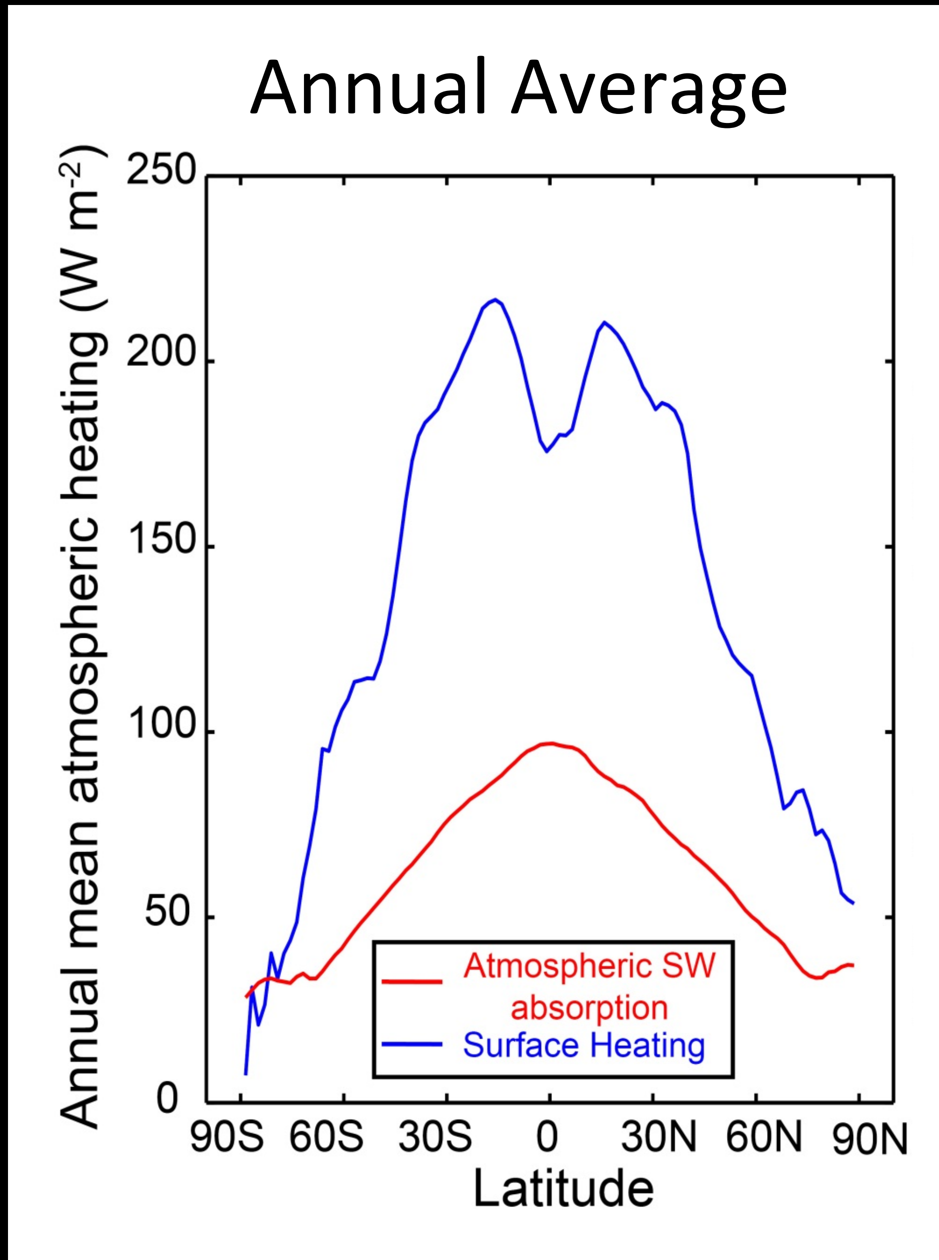


Surface energy balance (absorbed solar flux = upward flux to the atmosphere) requires that the ratio of heating from direct absorption to surface energy fluxes is approximately:

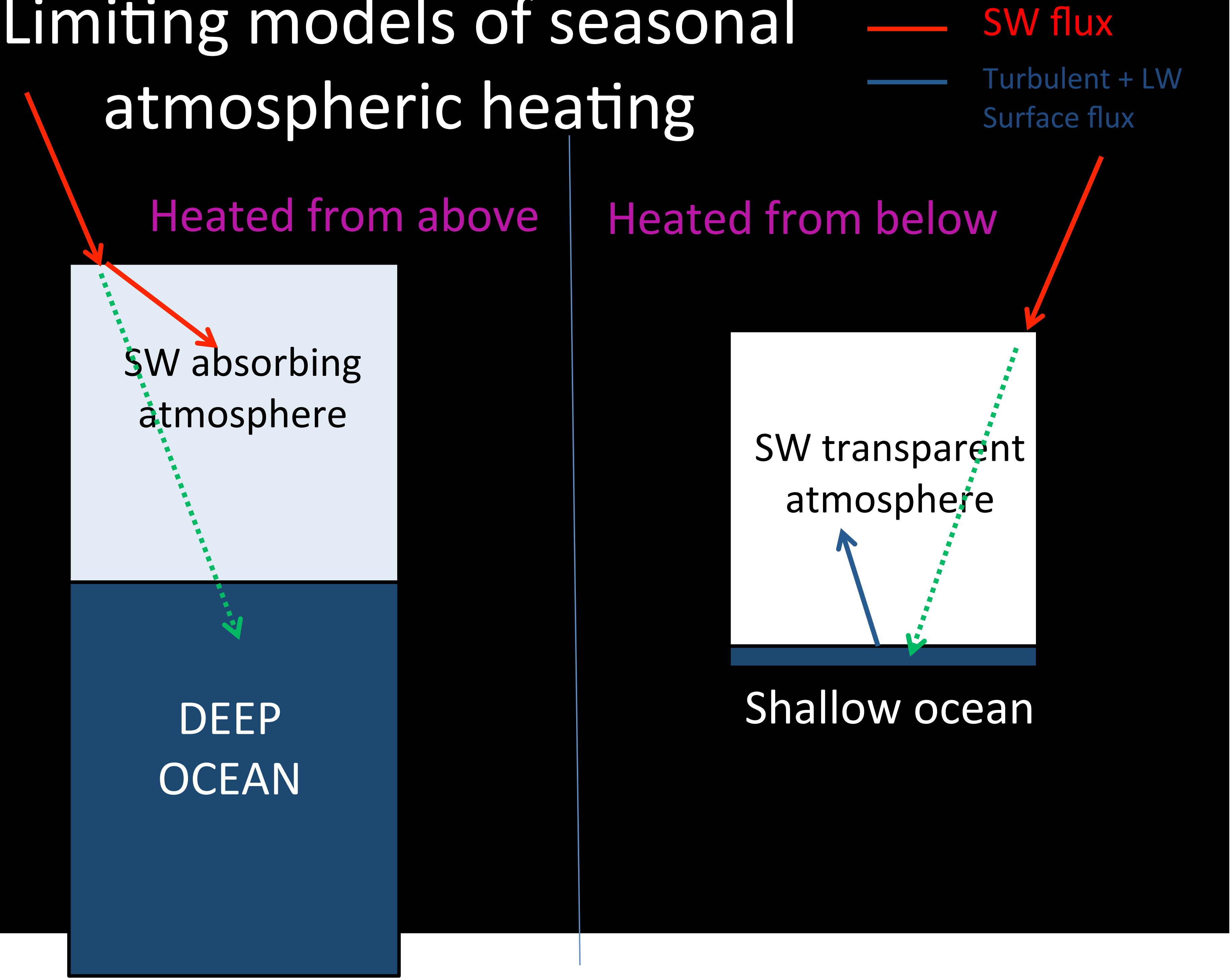
atmospheric absorption (SW) /atmospheric transmissivity(SW)

=> direct absorption accounts for 30% of atmospheric heating

Spatial structure of atmospheric heating

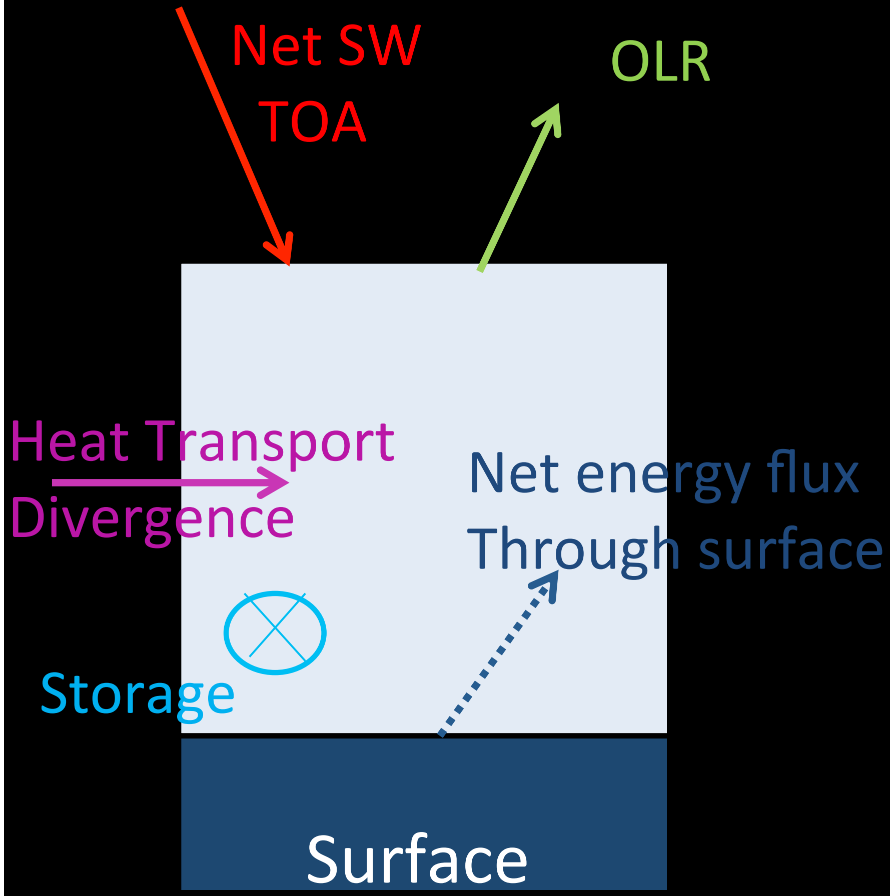


Limiting models of seasonal atmospheric heating



Atmospheric energy budget

Conventional



Net energy flux through surface =
Solar + turbulent + LW

Atmospheric energy budget -- Observations

$$\boxed{\frac{1}{g}\int_0^{Ps}\frac{dE}{dt}dP} = \boxed{SWABS} + \boxed{SHF} - \boxed{OLR} - \boxed{\frac{1}{g}\int_0^{Ps}\nabla\bullet\left(\vec{U}E\right)dP}$$

Storage

Heat Transport Divergence

$$\boxed{SWABS = SW\downarrow_{TOA} - SW\uparrow_{TOA} + SW\uparrow_{SURF} - SW\downarrow_{SURF}}$$

$$SHF = SENS\uparrow_{SURF} + LH\uparrow_{SURF} + LW\uparrow_{SURF} - LW\downarrow_{SURF}$$

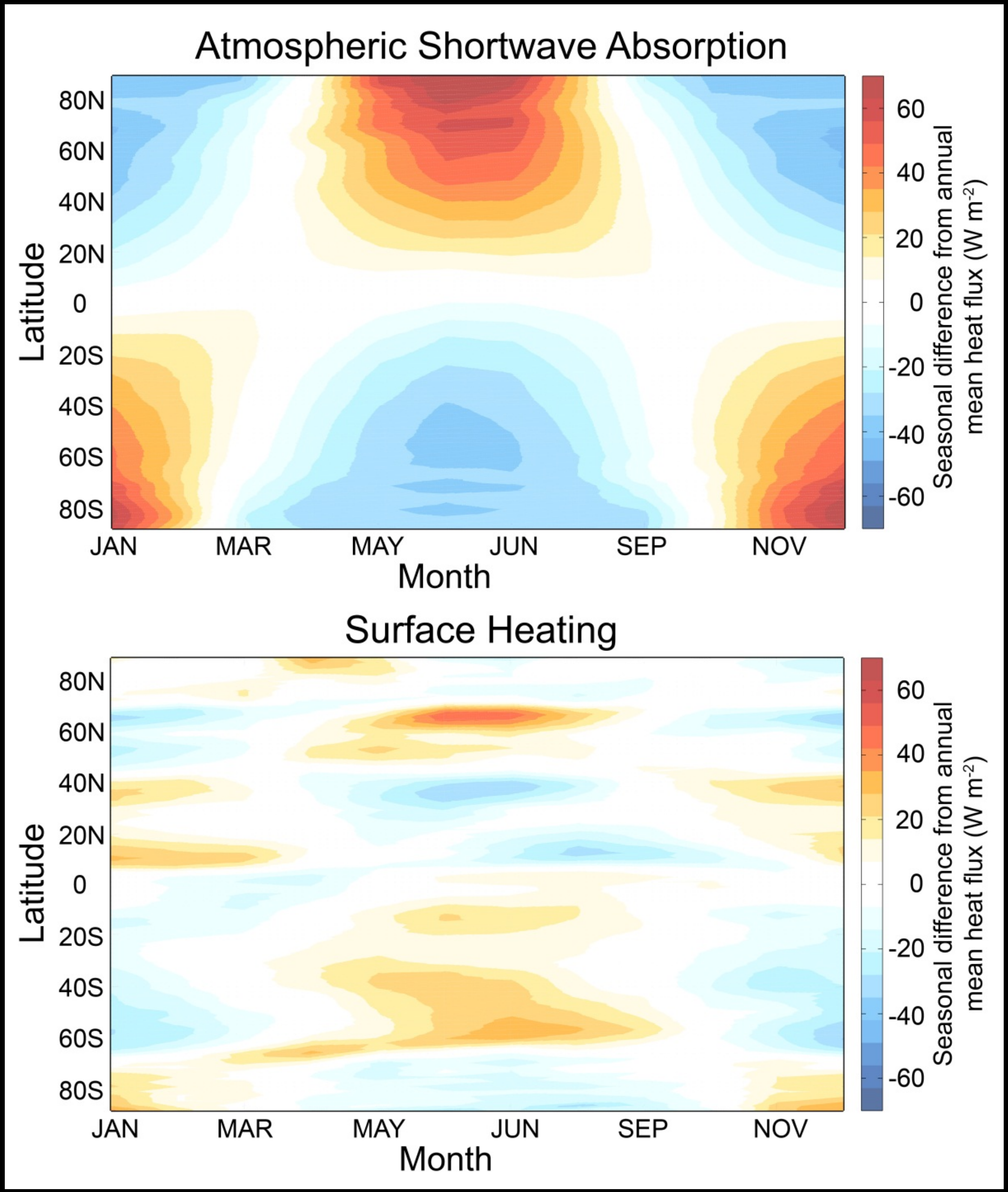
Radiative Fluxes from CERES

Dynamic fluxes and storage are calculated from ERA-40 reanalysis

Atmos. Surface exchange (SHF) as RESIDUAL

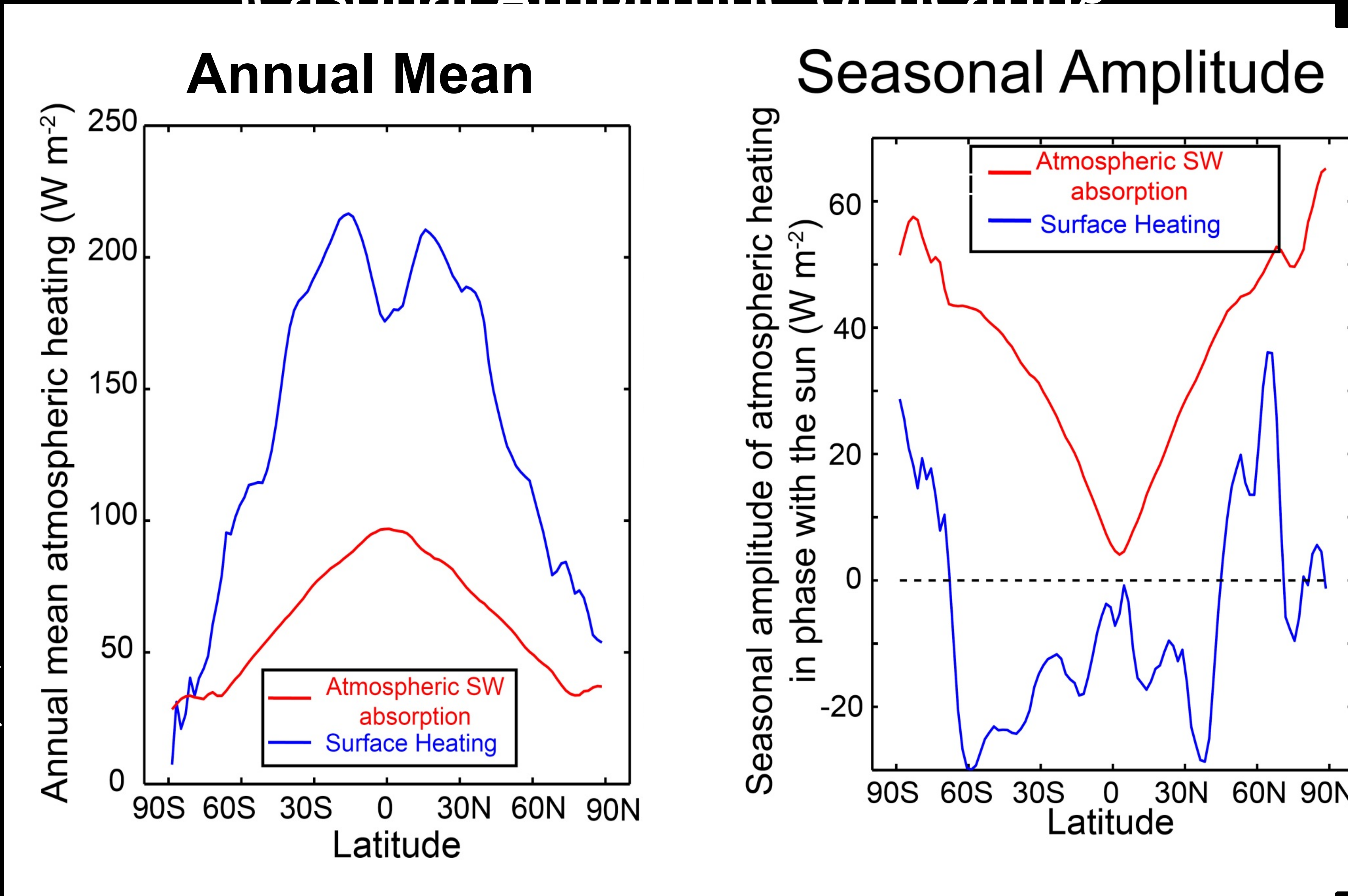
Seasonal Atmospheric Heating

ANNUAL MEAN IS REMOVED



Seasonal Amplitude of heating

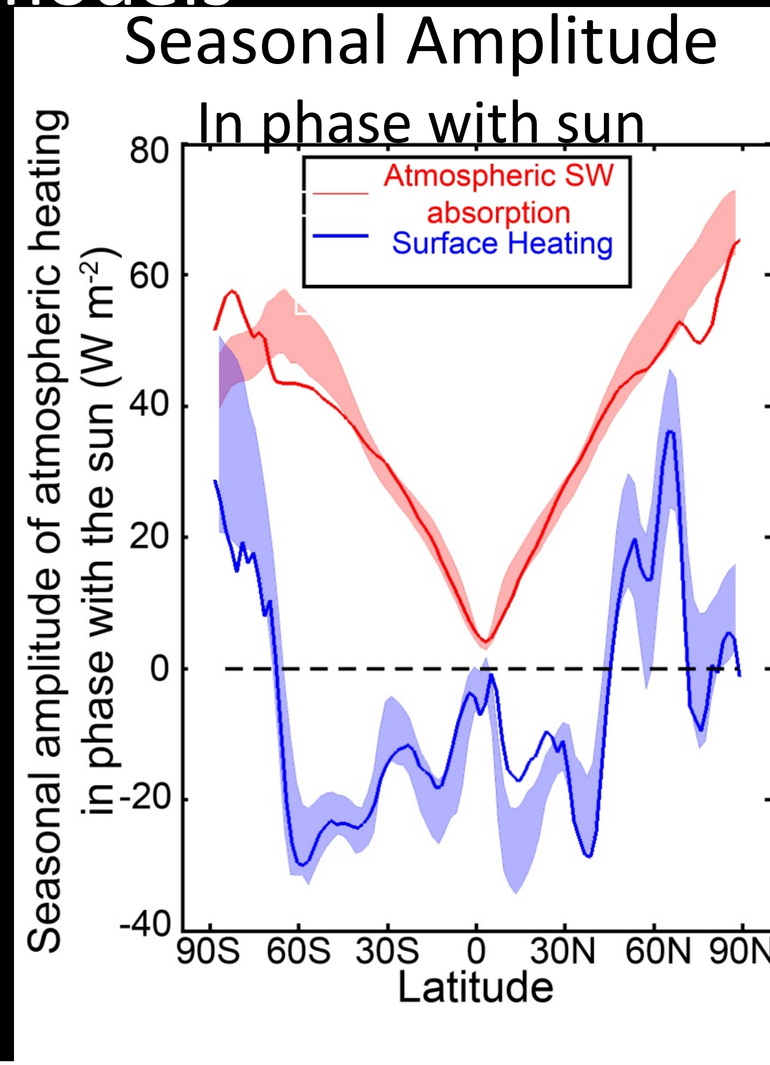
⇒
⇒



The seasonal heating of the atmosphere in climate models

Surface fluxes and shortwave absorption are calculated directly from model output

Atmospheric heat transport as a residual

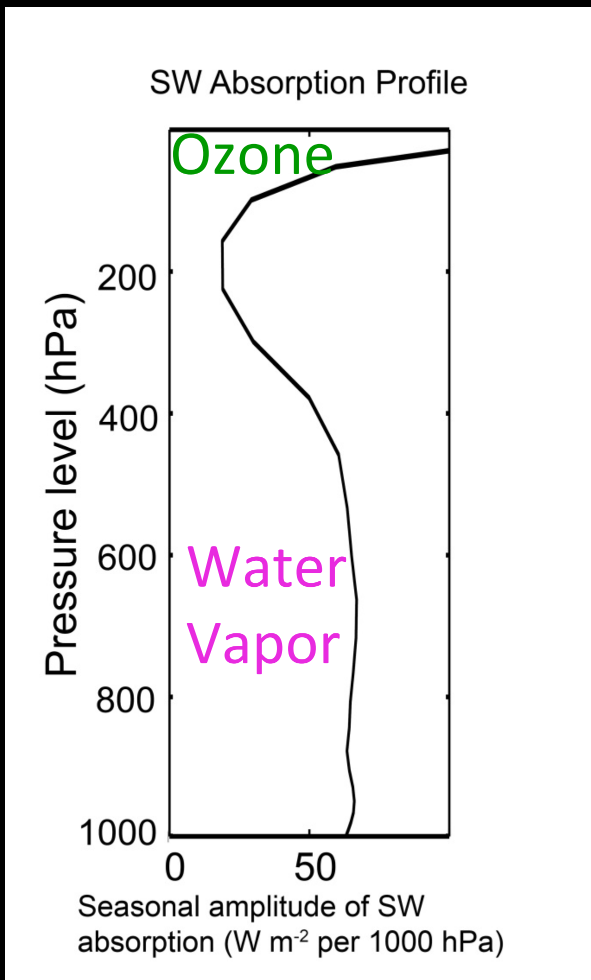


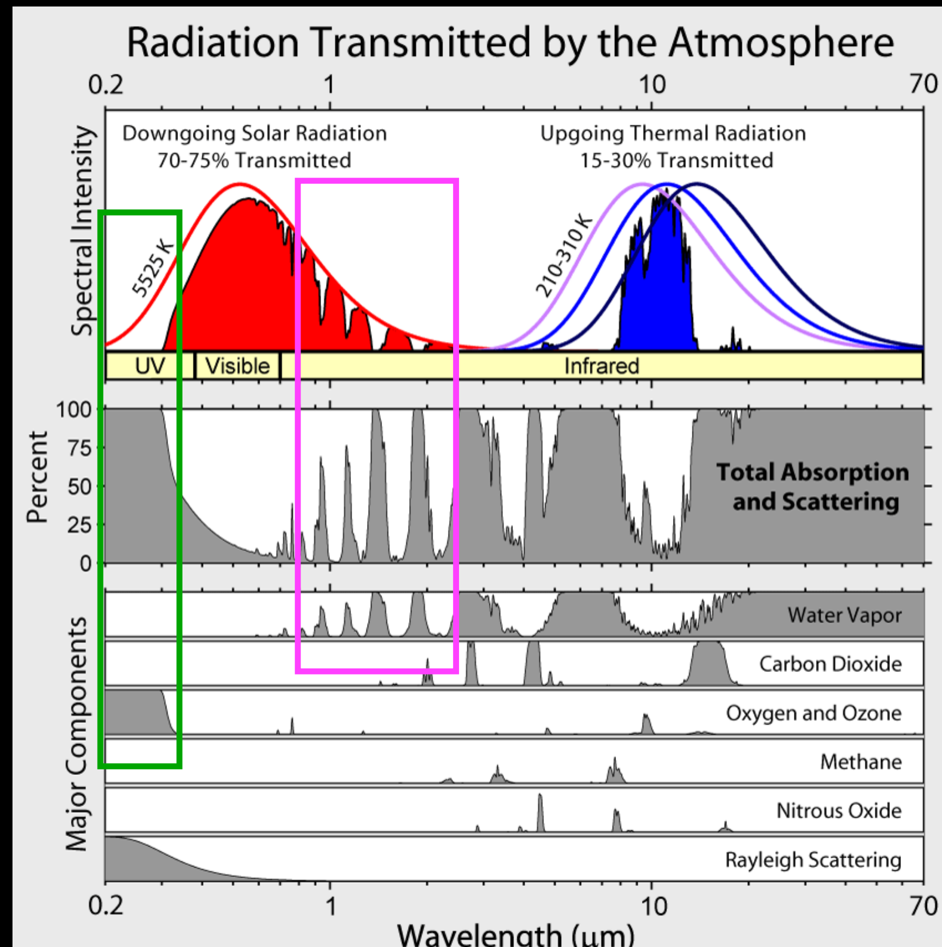
=> Solid lines = observations

=> Shading is ±1σ about CMIP3 ensemble mean

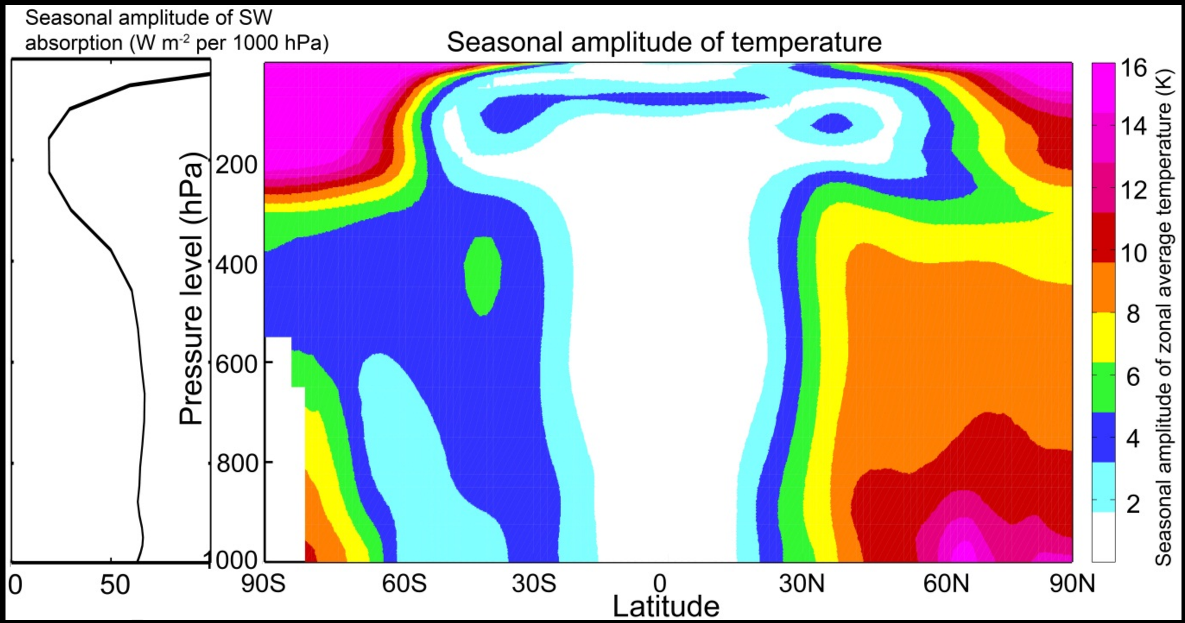
Vertical structure of SW absorption

GFDL Model
Seasonal amplitude
In the extratropics



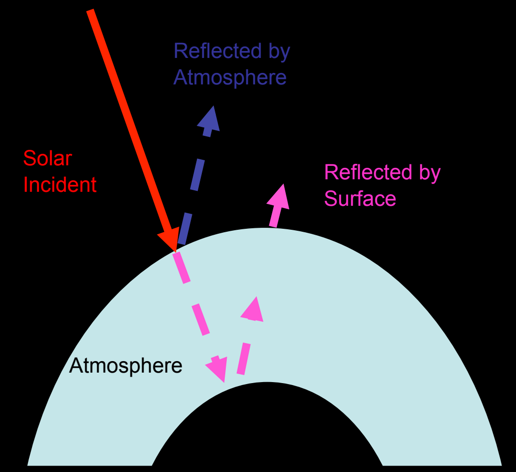


Structure of seasonal amplitude in temperature

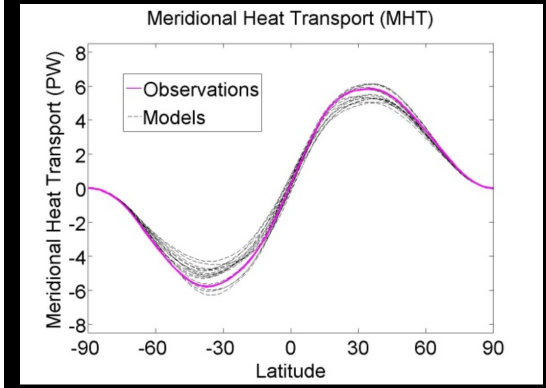


Seasonal cycle is surface amplified where the surface heat fluxes contribute to seasonal heating (over land)

Conclusions

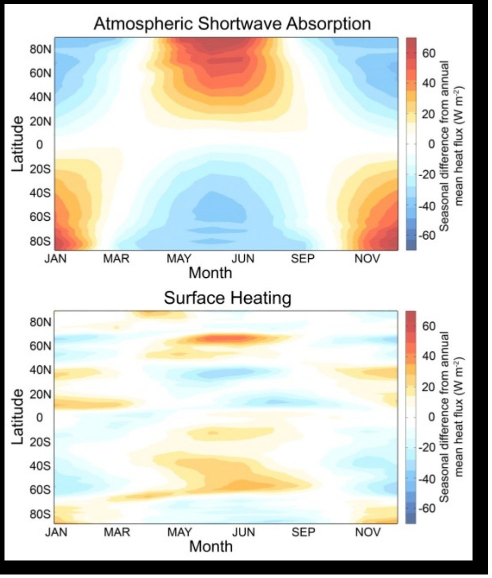


1. Global mean planetary albedo is primarily (88%) due to atmospheric reflection and only secondarily (12%) due to surface reflection
   -> Climatology and model spread
   -> Hemispheric contrast in planetary albedo sets ITCZ location



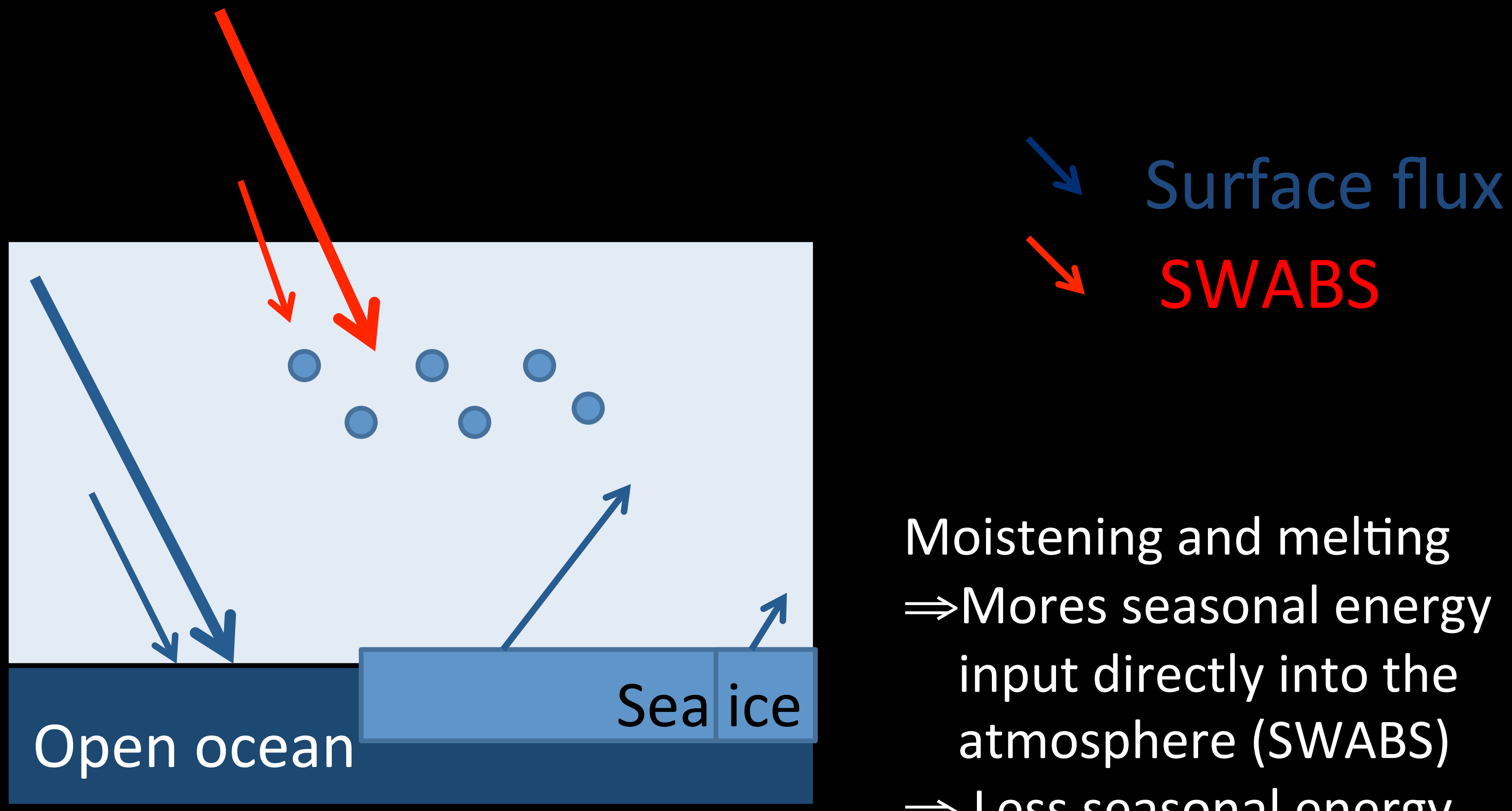
2. Poleward energy transport varies by 20% in climate models and is a consequence of simulated clouds

3. The seasonal heating of the atmosphere is due to shortwave heating of the atmosphere and is opposed by surface fluxes (contrast to annual mean)

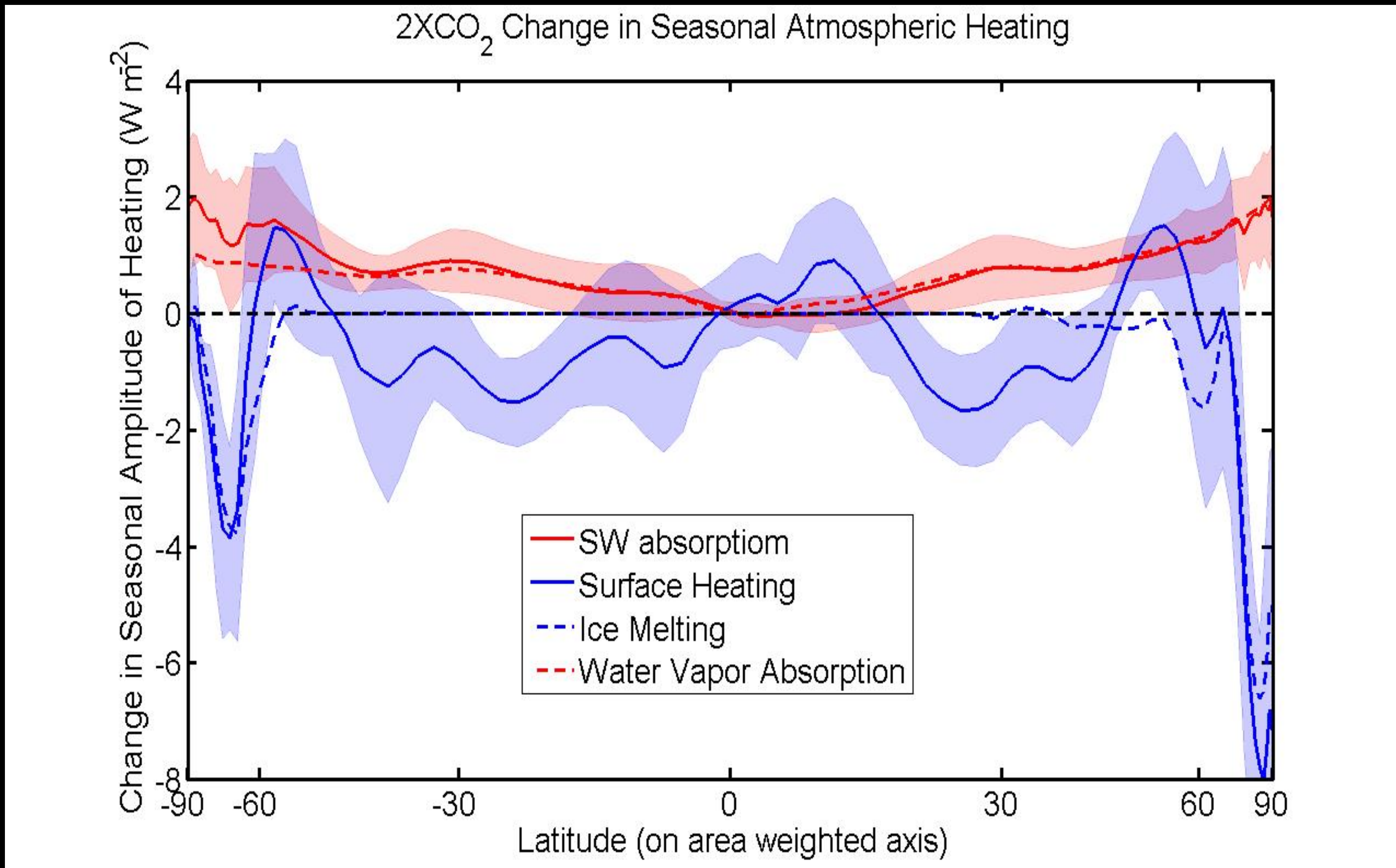


Extras

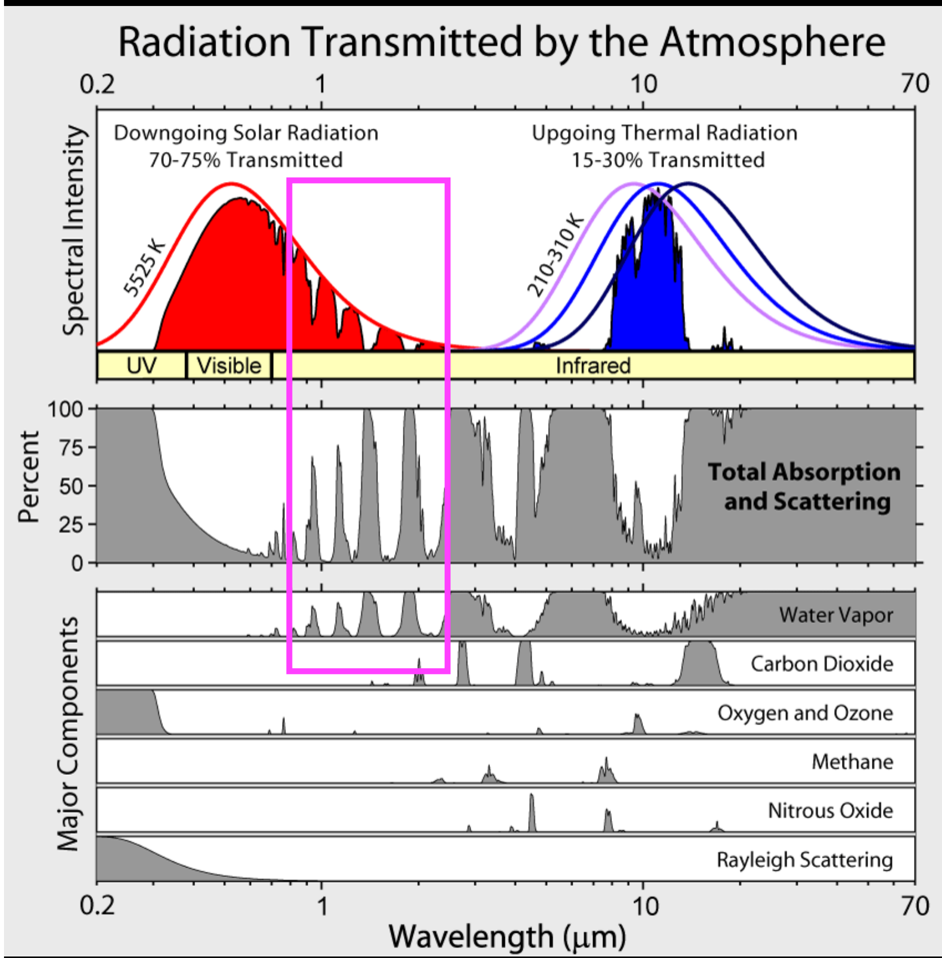
CO_2 doubling expectations
Summer schematic

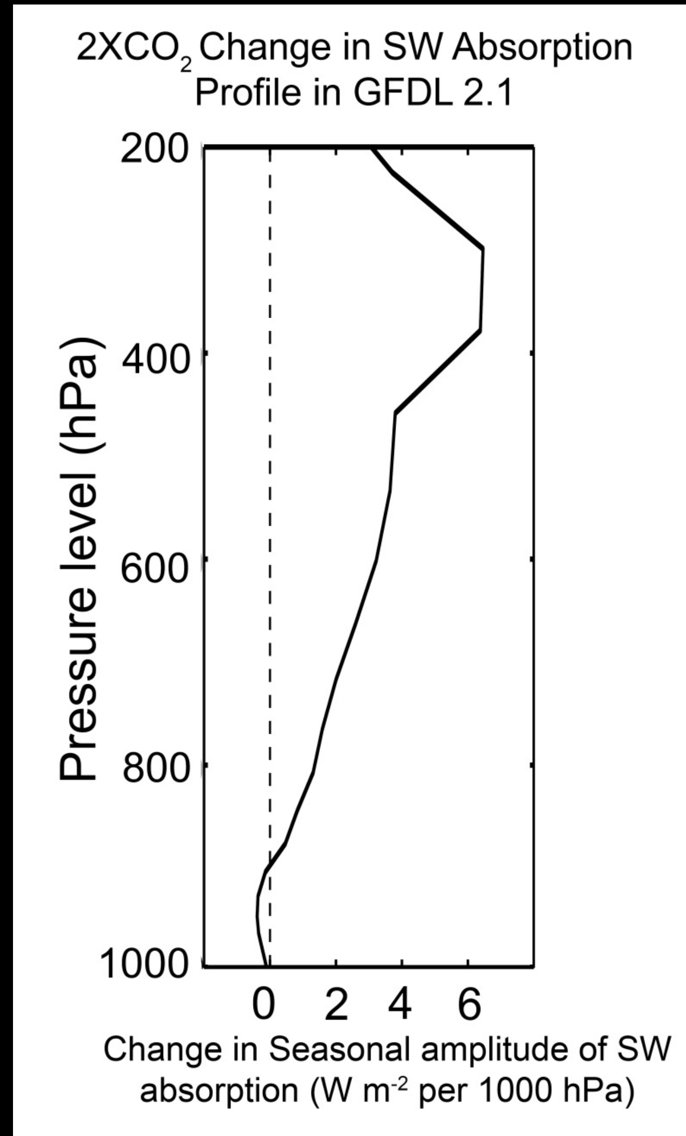


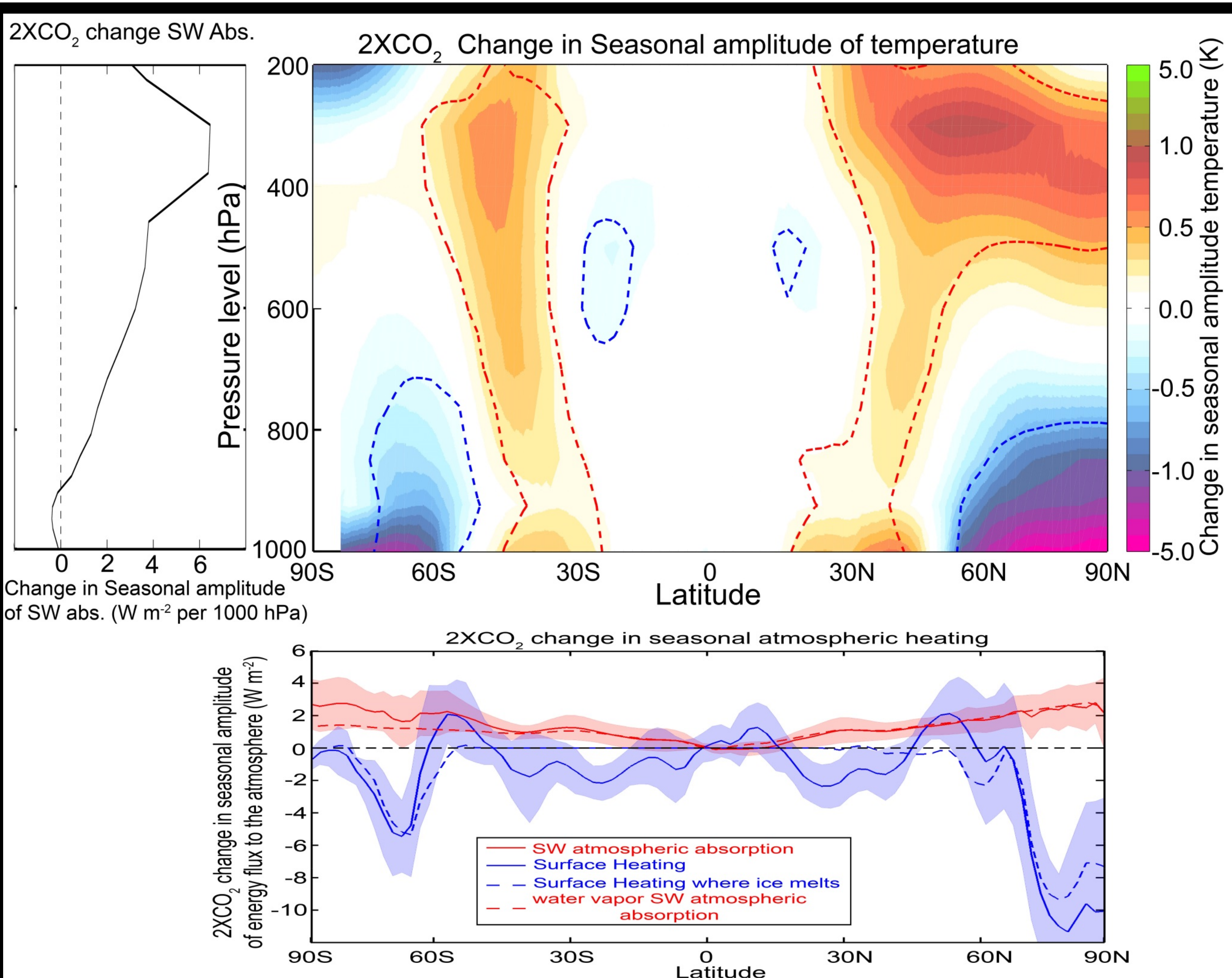
Moistening and melting
⇒Mores seasonal energy input directly into the atmosphere (SWABS)
⇒ Less seasonal energy input at the surface (SHF)


2XCO$_2$ Change in Seasonal Atmospheric Heating
Change in Seasonal Amplitude of Heating (W m^{-2})
4
2
0
-2
-4
-6
-8
-90
-60
-30
0
30
60
90
Latitude (on area weighted axis)
SW absorptiom
Surface Heating
Ice Melting
Water Vapor Absorption

Water Vapor as a SW Absorber

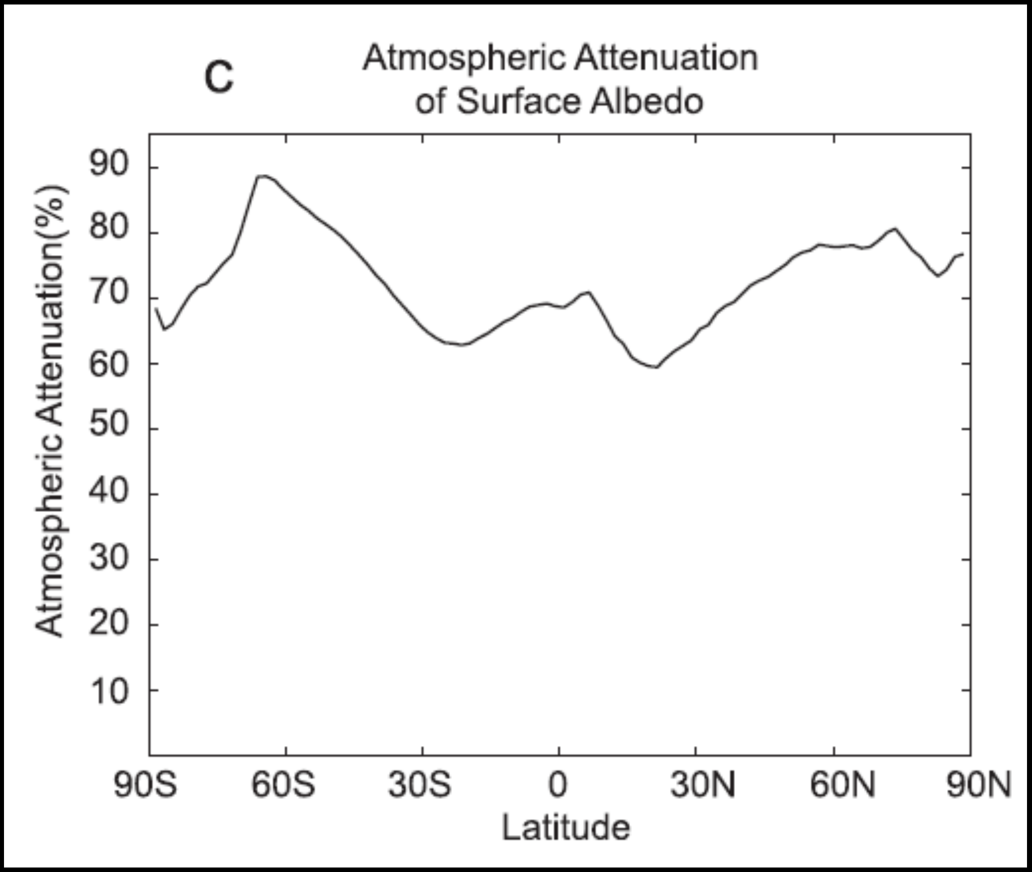




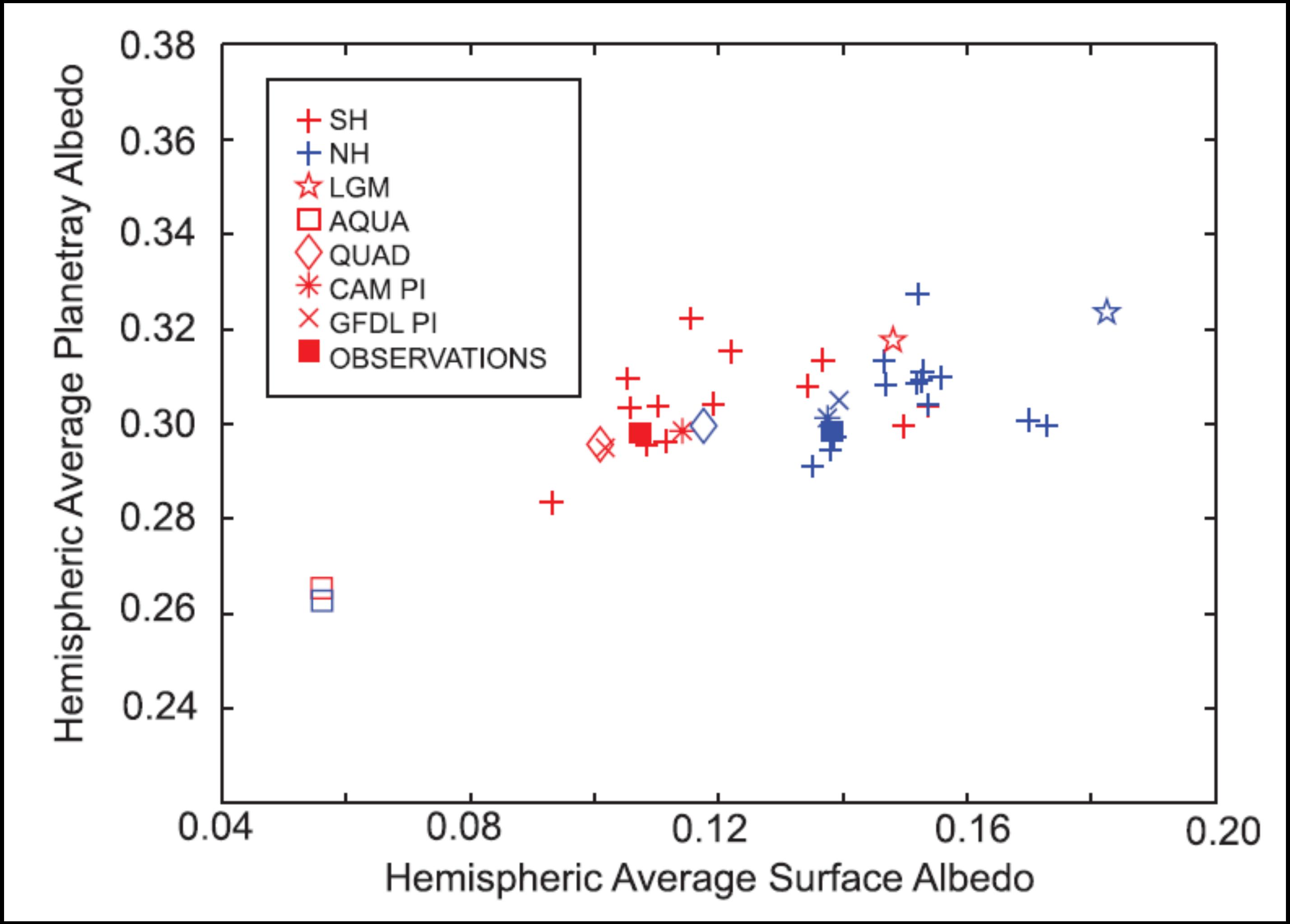


2XCO2 change SW Abs.
0
2
4
6
Change in Seasonal amplitude of SW abs. (W m-2 per 1000 hPa)
2XCO2 Change in Seasonal amplitude of temperature
Pressure level (hPa)
200
400
600
800
1000
90S
60S
30S
0
30N
60N
90N
Latitude
5.0
1.0
0.5
0.0
-0.5
-1.0
-5.0
Change in seasonal amplitude temperature (K)
2XCO2 change in seasonal atmospheric heating
2XCO2 change in seasonal amplitude of energy flux to the atmosphere (W m-2)
6
4
2
0
-2
-4
-6
-8
-10
SW atmospheric absorption
Surface Heating
Surface Heating where ice melts
water vapor SW atmospheric absorption
90S
60S
30S
0
30N
60N
90N
Latitude

Meridional structure of atmospheric attenuation



Planetary Albedo and Surface Albedo



Meridional profile of albedo in all simiulations

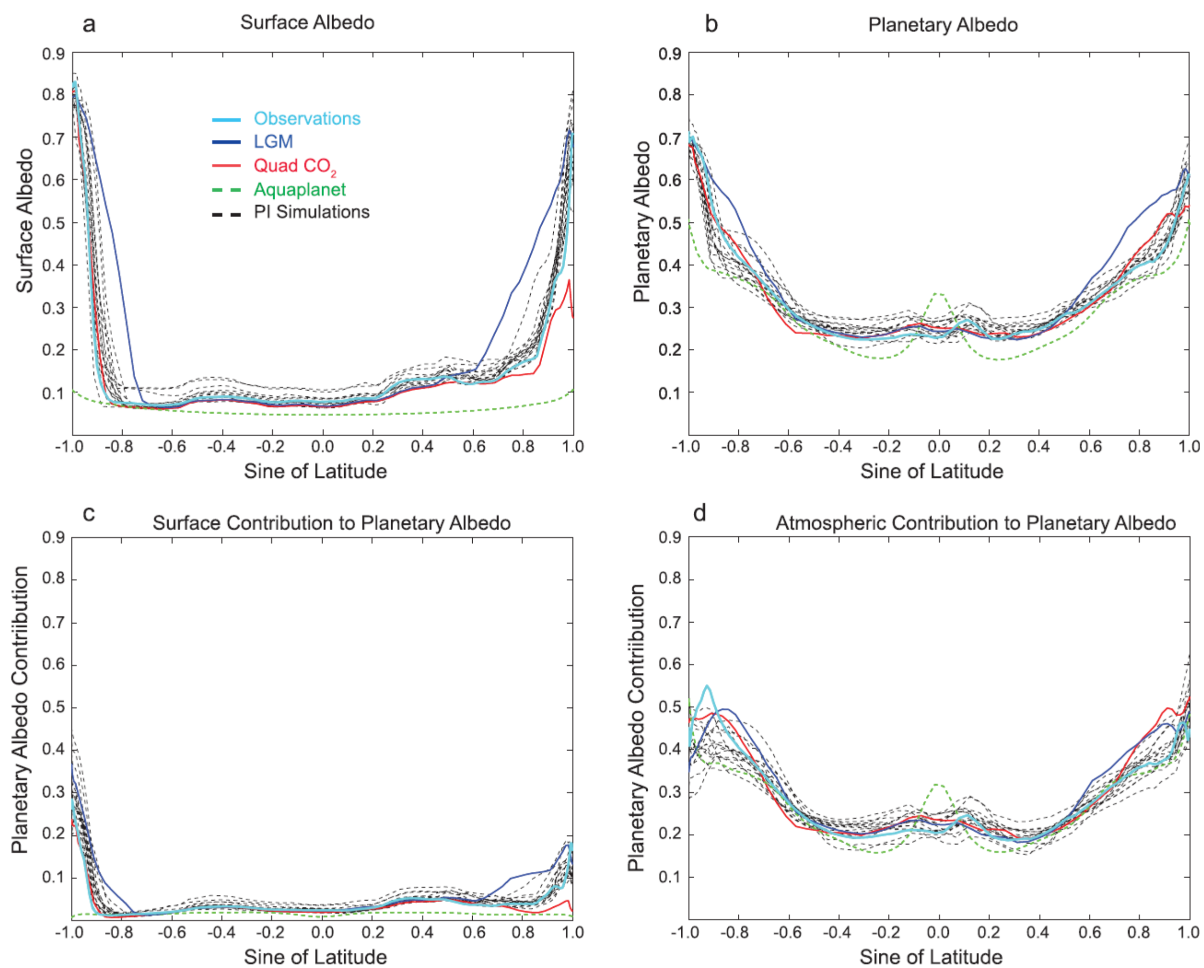
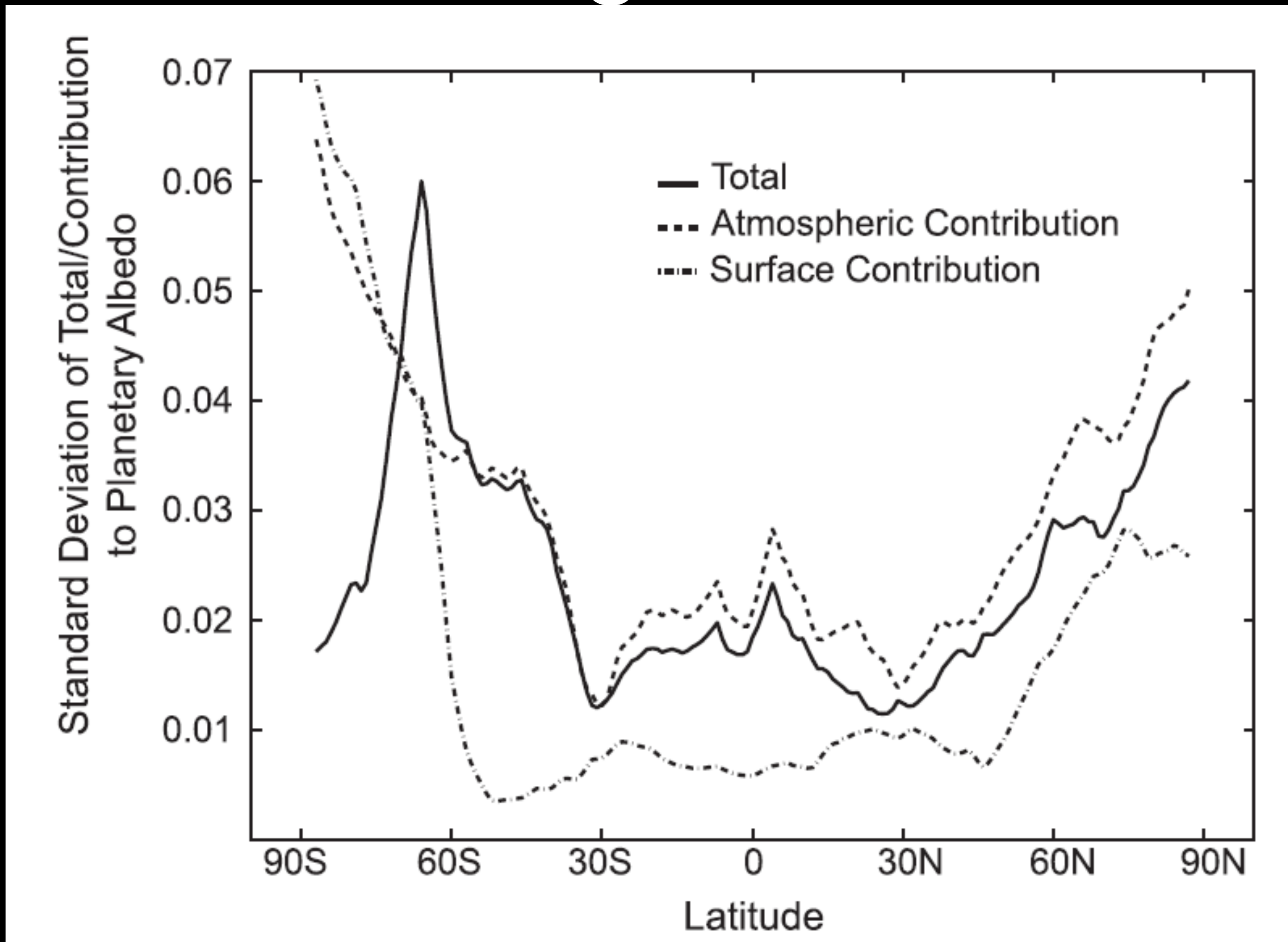
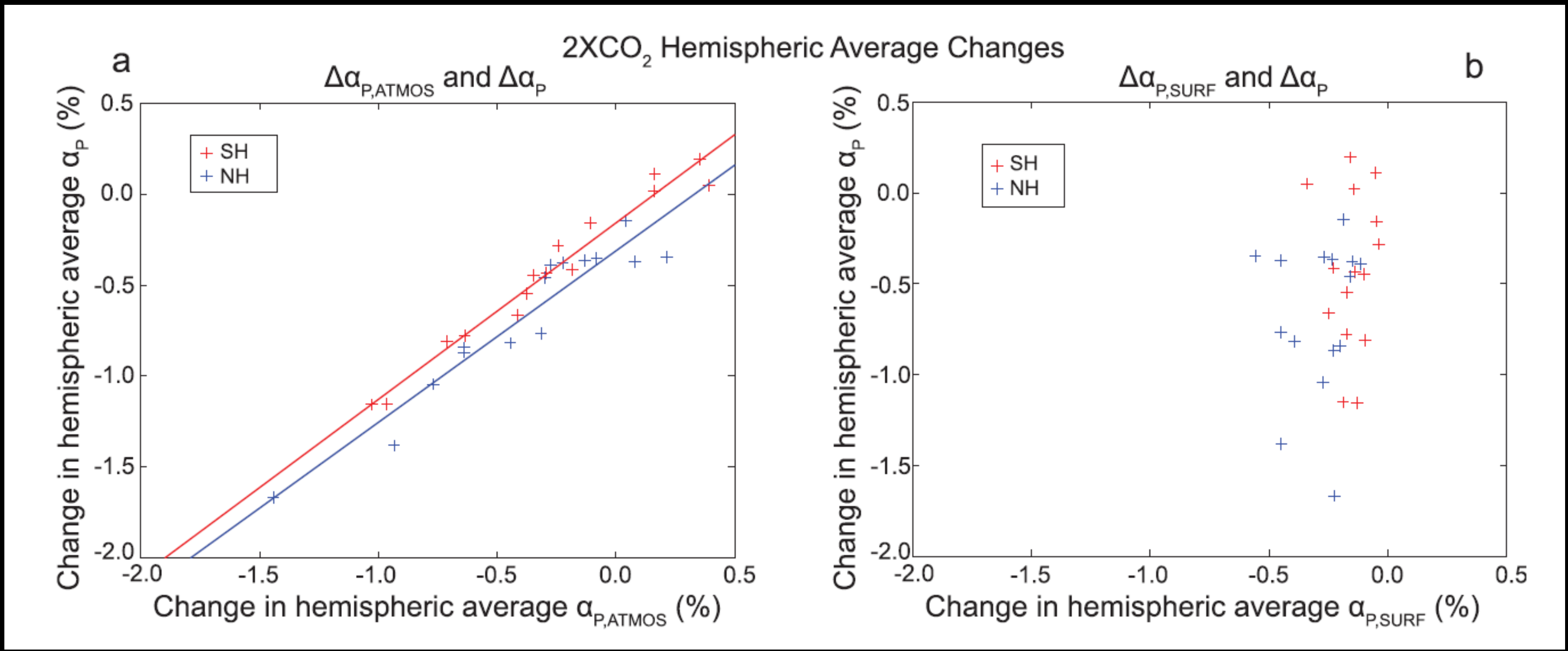


FIG. 6. Zonal annual mean (a) α, (b) α_P, (c) $\alpha_{P,\mathrm{SURF}}$, and (d) $\alpha_{P,\mathrm{ATMOS}}$ in the PI simulations from the CMIP3 models (dashed black lines). Also shown are the observations (solid light blue line) and model simulations of altered climate states (other colored lines).

Inter-model spread in albedo by region



$2XCO_2$ Planetary Albedo



2XCO$_2$ Planetary Albedo

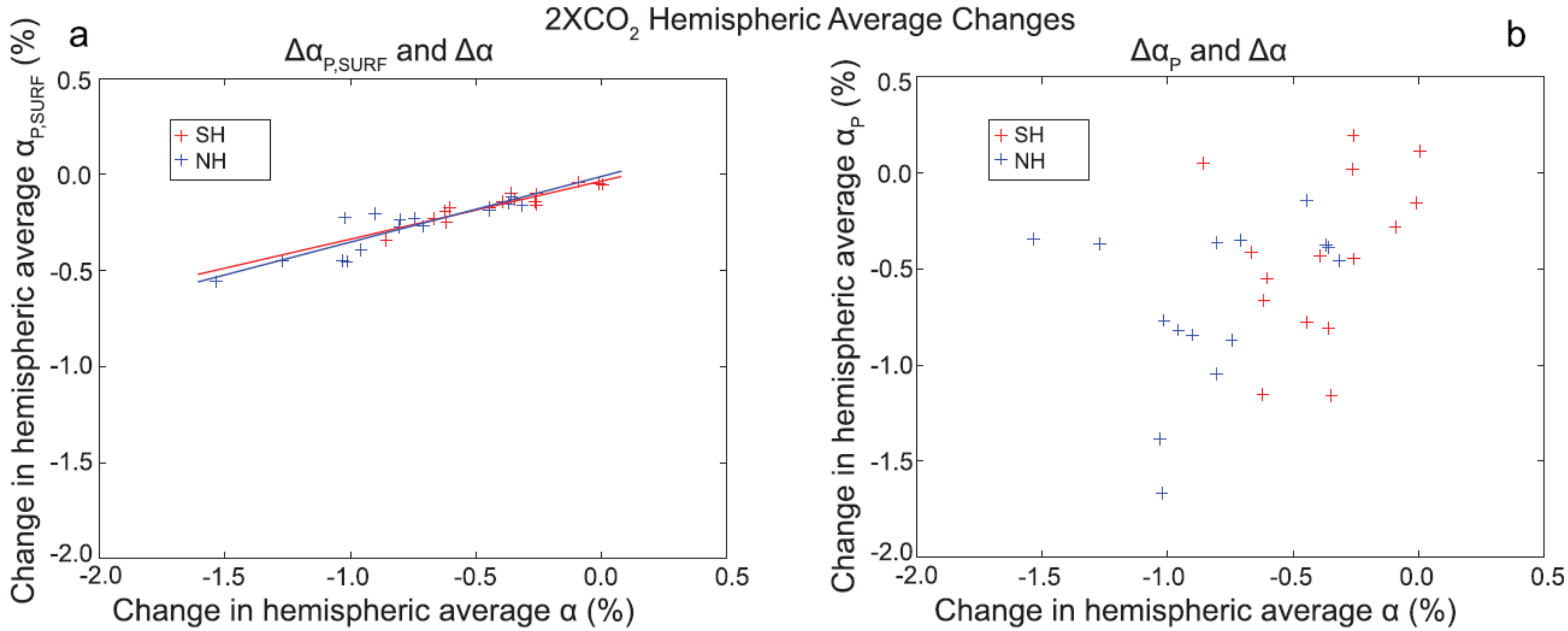
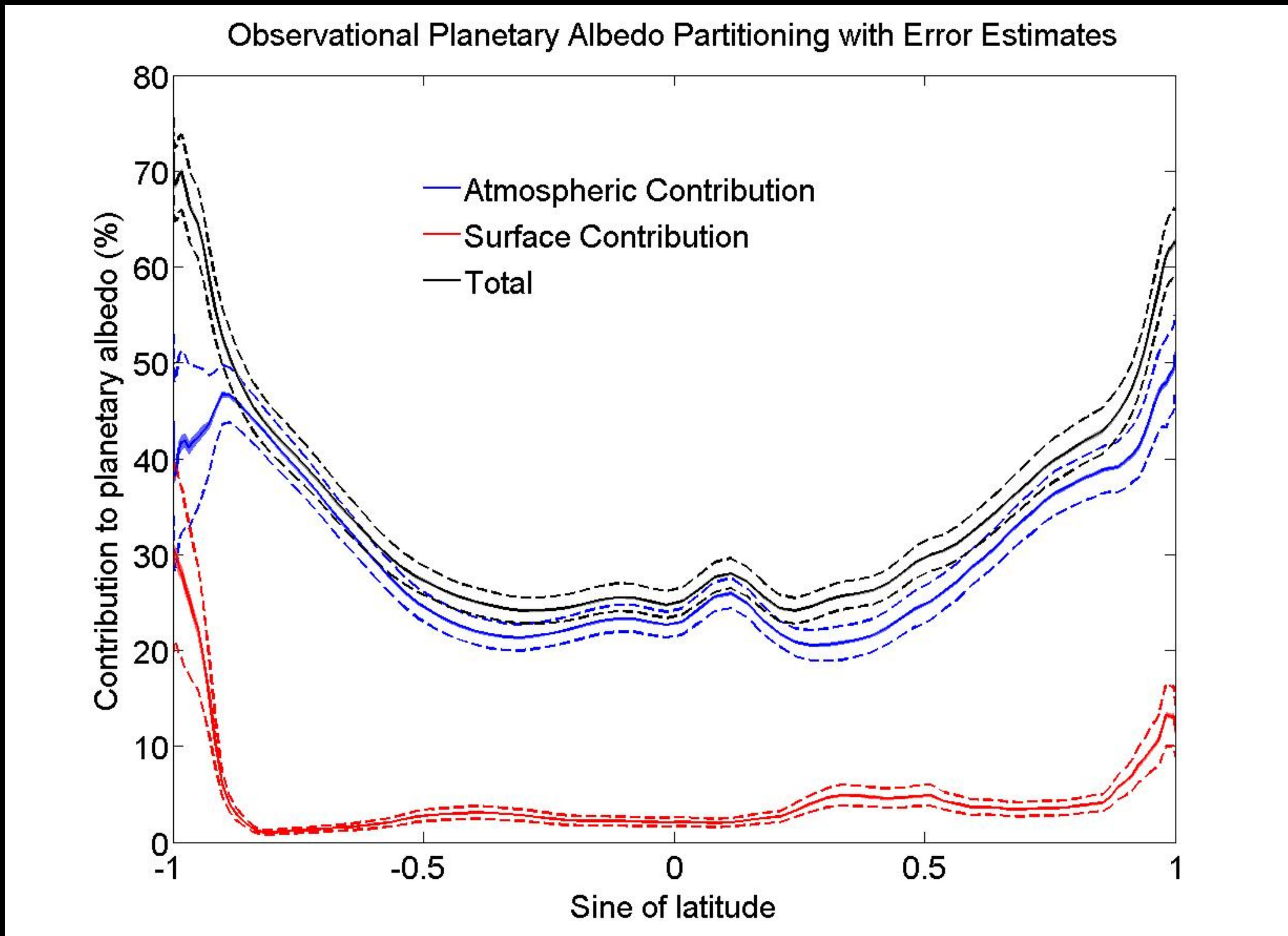
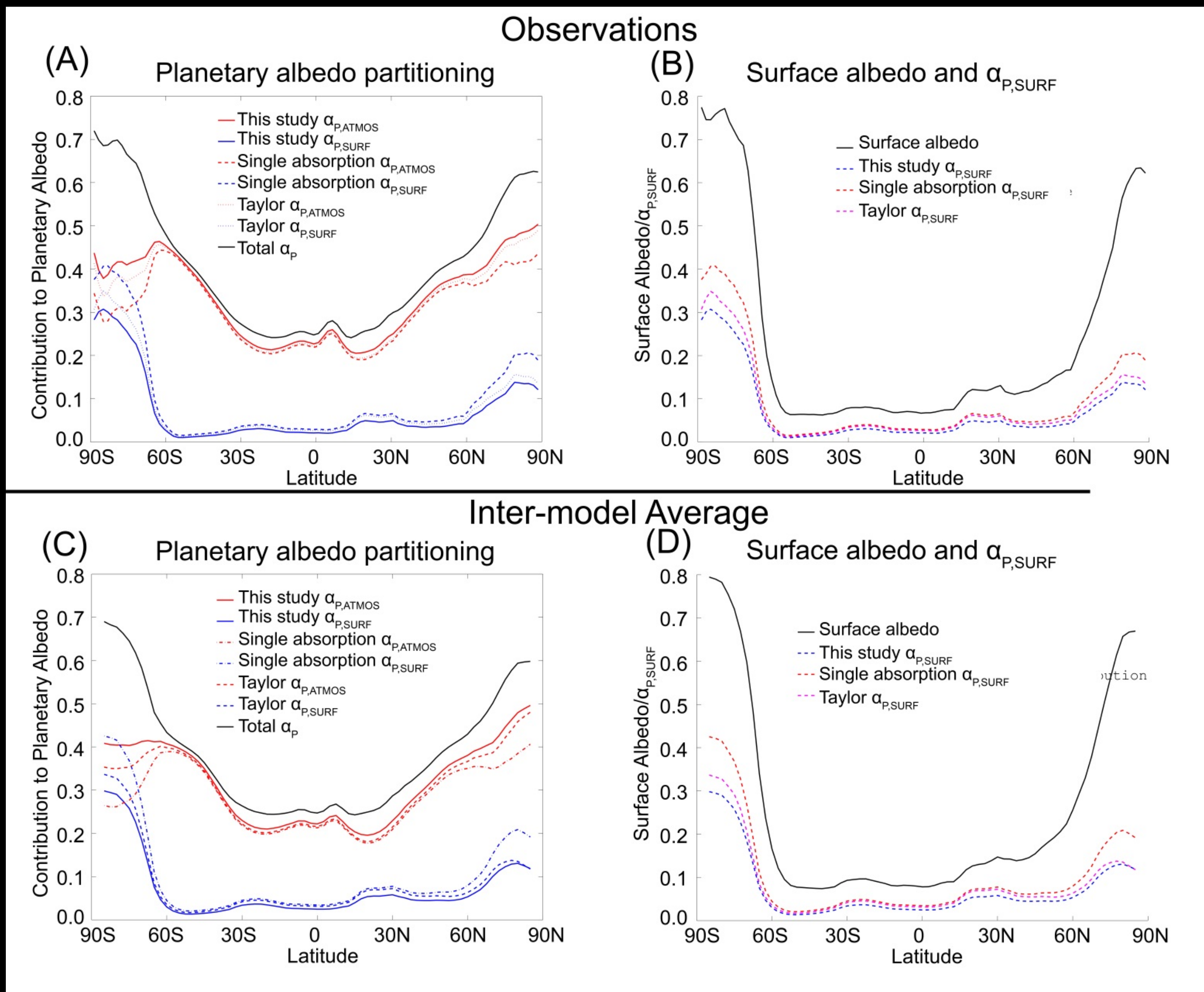


FIG. 9. (a) Change in hemispheric average $\alpha_{P,\mathrm{SURF}}$ in the $2 \times CO_2$ runs (relative to the PI simulations) vs change in hemispheric average α. The lines are the linear best fits in each hemisphere. (b) Change in hemispheric average α_P in the $2 \times CO_2$ runs (relative to the PI simulations) vs change in hemispheric average α.

Carl's Question: Planetary Albedo Partitioning Error Bars



Planetary Albedo Partition: Sensitivity to shortwave absorption assumptions

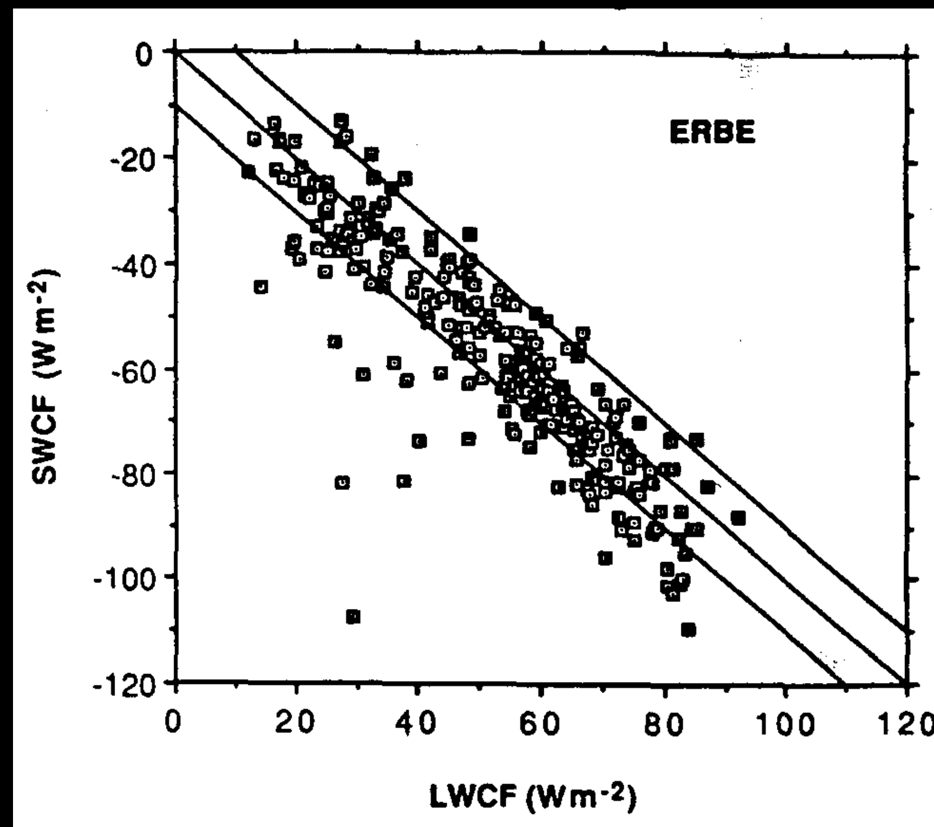


What determines OLR*?

Why don't differences in ASR* and OLR* compensate for each other?

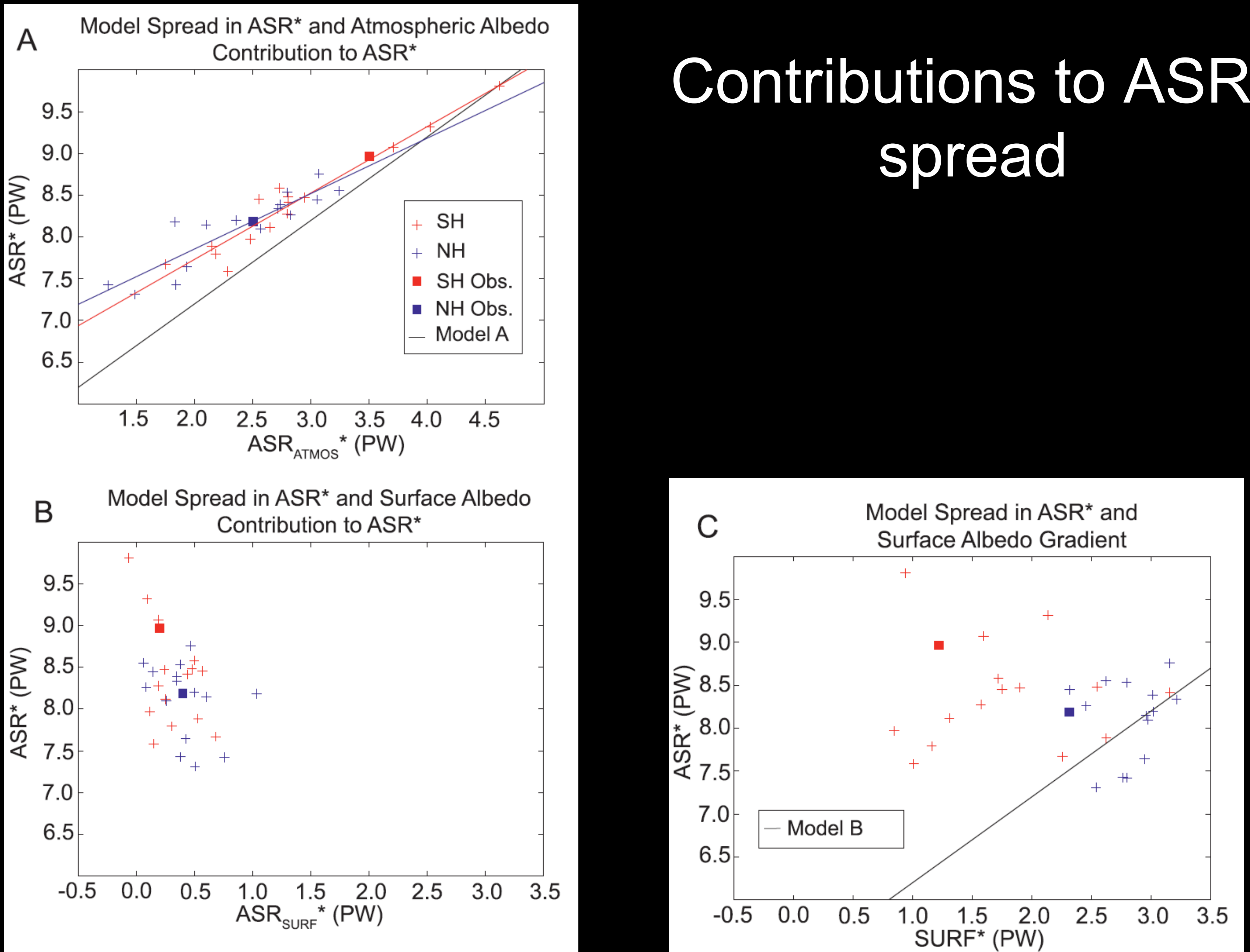
Longwave Cloud Forcing

$LWCF = OLR_{CLEAR} - OLR$

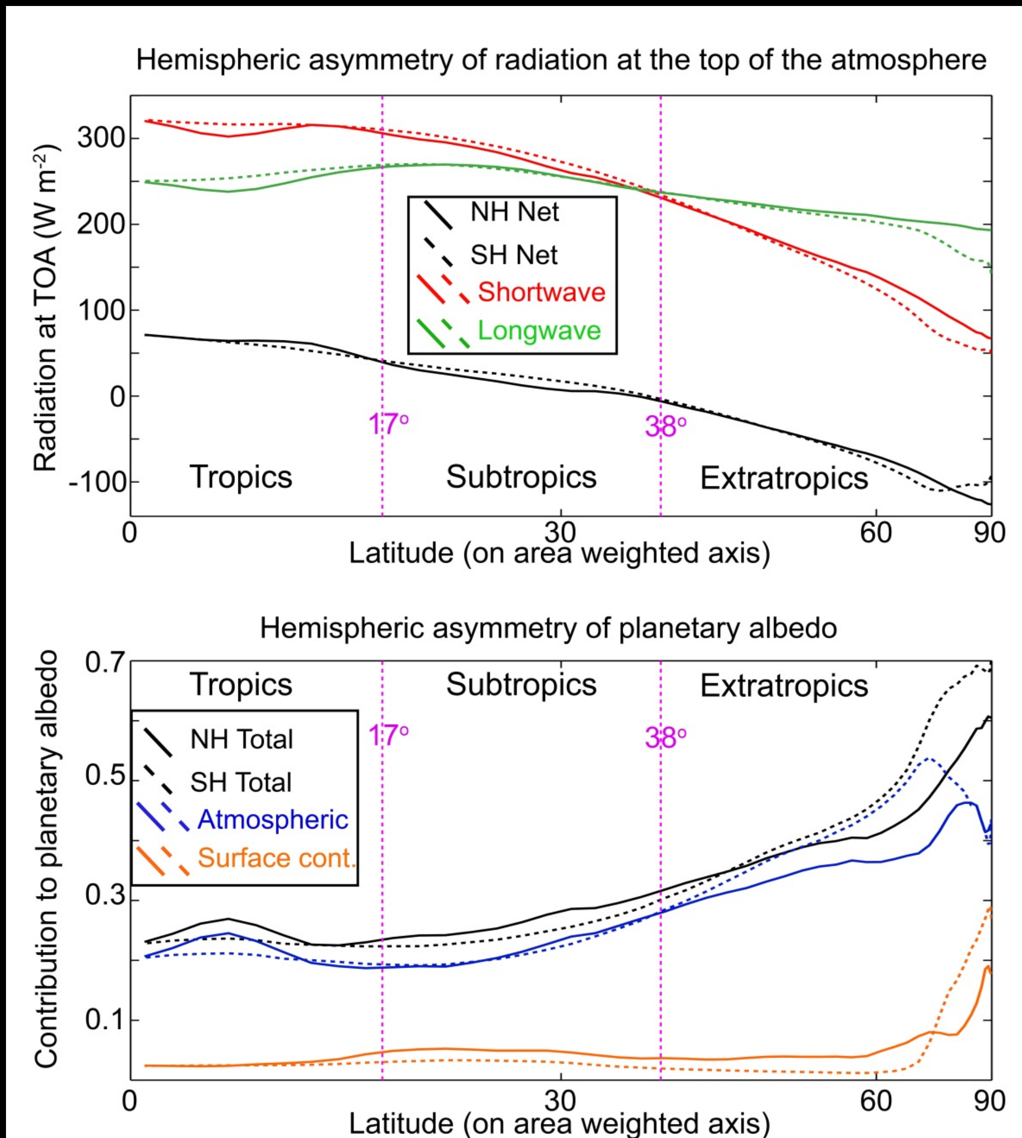


(Kiehl, 1994)

Contributions to ASR* spread



Hemispheric Contrast Of TOA Radiation



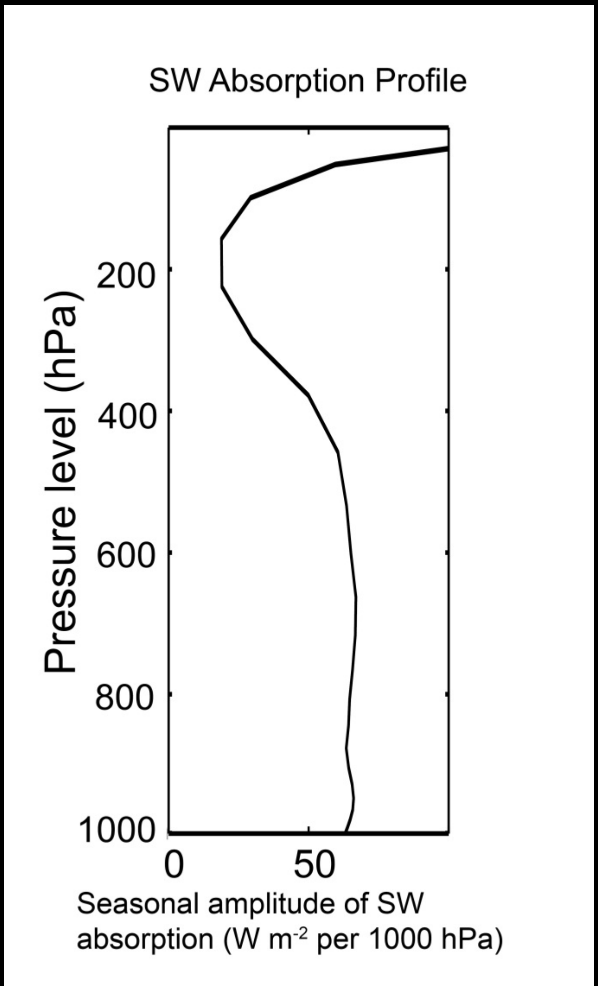
NH reflects more SW radiation in the subtropical deserts. SH reflects more SW in the extratropics due to clouds in the Southern Ocean

The NH is warmer (more OLR), especially in the polar latitudes

Planetary albedo is partitioned into cloud and surface contributions via the method of Donohoe and Battisti (2011)

Vertical structure of SW absorption

GFDL Model
Seasonal amplitude
In the extratropics



Chou Lee (1996)
Water vapor absorption
In the summer